electrical
engineering

HYDRO-ELECTRIC POWER

VOLUME II

ELECTRICAL EQUIPMENT
AND TRANSMISSION

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ELECTRICAL EQUIPMENT AND TRANSMISSION

BY

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PREFACE TO VOLUME II

This volume forms a companion to, and is, in fact, a continuation of Volume I. There is no definite point of division between the two volumes and this treatise was divided into two sections solely to make it less cumbersome and more convenient for reference.

The treatments of many of the subjects are new and some of the formulæ have never previously been published. Like Volume I, this book is founded on experience and accepted practice, and is in no wise an academic treatise.

The fundamentals of electric circuits, discussed from a physical instead of a mathematical standpoint, have been included after careful consideration, in the belief and expectation that this portion of the text will be useful and convenient for engineers who already understand the principles of electrical circuits and alternating currents. The author is glad to be enabled to include Mr. H. B. Dwight's chart for the solution of transmission line problems, as it constitutes an admirable method of quick computation and saves both time and labor.

With the generally accepted practice of using steel towers for transmission lines, the author is compelled to take issue. The economical reasons for supporting transmission lines on wood or concrete poles in preference to steel towers seem clear and unescapable. That the short discussion on this subject will turn the tide of conventional design from a practice which seems almost universal, is not to be expected and, undoubtedly, the use of steel towers will still continue. For the use of such engineers as prefer conventionality to economy, a complete discussion of steel towers is included.

Much labor has been expended in an attempt to make all mathematical discussions clear and simple. Wherever equations are given, the significance of the symbols used will be found in close proximity to the equation.

In the preparation of this book, the author has received valuable assistance from several sources for which he takes

pleasure in expressing his appreciation. To Dr. A. S. Chessin, who read the manuscript and has made important suggestions and criticisms, the author is particularly indebted.

Also, the assistance of Mr. F. G. Switzer, who furnished much of the material for the chapters on Generators and Transformers, and of Mr. J. B. Shelby, who supplied many of the data for the chapter on Switchboards, is here acknowledged. Certain of the manufacturing companies have supplied many helpful data and cuts, and their names are mentioned in the text in connection with the descriptions of their apparatus and devices.

LAMAR LYNDON.

NEW YORK,
September, 1916.

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HYDRO-ELECTRIC POWER

VOLUME II

CHAPTER I

ALTERNATING-CURRENT GENERATORS

The form of alternating-current generator now in general use is the revolving-field type. This machine consists of a revolving-field member and a stationary armature.

The revolving-field member, or "rotor," is a cast-steel spider on the periphery of which are a number of equally spaced, radially projecting poles. The number of poles depends on the speed at which the machine is to run and the frequency of the system. Thus, the product of the number of poles and the revolutions per minute, of the rotor is equal to 120 times the frequency in cycles per second.

Also, if p = number of poles.

$$p = \frac{7200}{\text{r.p.m.}}, \text{ for 60-cycle machines.}$$

$$p = \frac{3000}{\text{r.p.m.}}, \text{ for 25-cycle machines.}$$

$$\text{r.p.m.} = \frac{7200}{p}, \text{ for 60-cycle machines.}$$

$$\text{r.p.m.} = \frac{3000}{p}, \text{ for 25-cycle machines.}$$

An 18-pole, 60-cycle generator, therefore, runs at 400 r.p.m.

On machines of comparatively small diameter, the poles are cast integral with the spider or hub. Large-diameter machines may have a cast-iron or cast-steel spider with a cast-steel rim, separate poles being bolted or dovetailed onto the rim. On each of the poles is a winding consisting of strip copper wound on edge. In making these coils the copper is first bent to shape, and then each turn is insulated from the next with treated paper or other thin insulating fabric. The whole coil is insulated from

the pole on which it is placed, with heavy paper or other fibrous material, or mica. All of the windings are connected in series, and the two final ends of the windings are connected to collector rings mounted on the generator shaft. The field current, or exciting current, is lead to the rotor through these collector rings on which brushes rest. The brushes are held in place by suitable brush rigging mounted either on the pedestal or on some

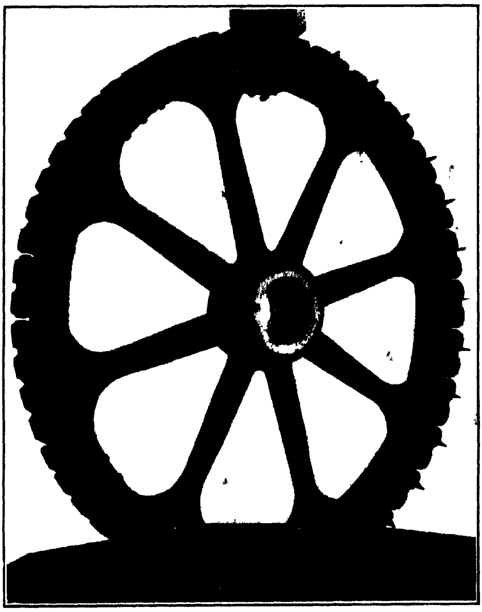

FIG. 1.—Revolving field of alternator.
500 k. v. a., 3 phase, 120 r. p. m., Crocker-Wheeler Co.
Showing ventilating rings

independent foundation. The brushes are usually made of carbon. The brush rigging should be of rigid construction and the number of brushes per collector ring such that if one brush does not make contact or is for any reason removed, the other brushes will carry the total current without serious overheating. The conductivity of brushes will vary so much with their composition that no general statement can be made in regard to the carrying capacity.

Direct current is used for excitation. The usual voltage of

the direct-current exciting circuit is 125 volts, although 250 volts is also common and standard. It is better to proportion the coils for 125-volt excitation since it is possible to design a cooler rotor winding, or one capable of carrying overloads at low power factor for this lower voltage. Fig. 1 shows a complete rotor.

The rotor and stator are separated by a short clearance called the air gap.

The armature, or "stator," consists of a cast-iron frame carrying a soft-steel core, with its windings and protecting

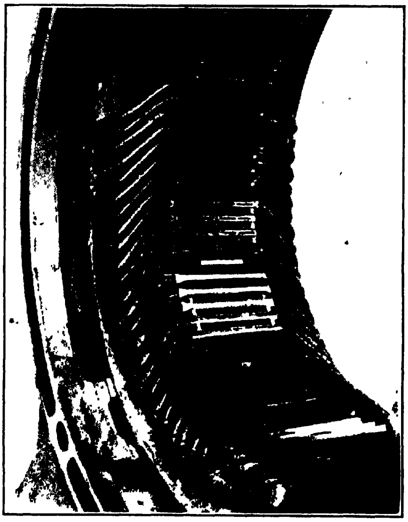

FIG. 2.—Portion of stator partly wound.

shields. The frame is nothing more than a support for the stator. The core is made up of thin laminations of punched steel securely fastened in the frame. The armature coils are placed in slots in the inner periphery of the core. Each coil is made of insulated copper wire, or strip, wound on a simple form, stretched to the proper shape, and before being placed in the slots, is insulated with treated paper, treated cotton, or other fibrous material, the whole thoroughly soaked with a good insulating varnish and baked until dry. In some machines where a high temperature is to be expected, asbestos is used in

the insulation. On coils for extra high voltage, the insulation is of mica. The coils are held in the slots by slot wedges of wood, fiber, iron, or steel, which are placed in grooves in the inner edges of the teeth. Fig. 2 shows a portion of a stator core, partially wound. Fig. 3 shows a completely assembled machine. The shields are merely a protection to the windings, preventing injury from external sources, as well as preventing the attendants coming into contact with the windings. They also serve to direct the ventilating air which cools the machine. Fig. 4 shows the end and side elevations of a machine, sectioned to show the parts.

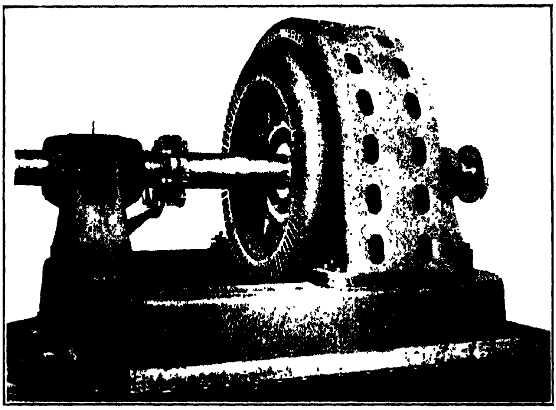

Fig. 3.—Revolving field generator.

The choice of generator voltage depends somewhat on the transmission-line voltage. Up to about 13,000 volts, the generators may be connected directly to the line without the interposition of transformers. The capacity of a generator wound for a voltage of 13,000 volts is, perhaps, 30 to 40 per cent. lower than the same machine wound for 2300 volts maximum. This is due to the fact that more insulation is necessary for the higher voltage, and the space that this insulation takes is utilized in the lower-voltage machine for active steel or copper. When it is possible to choose a voltage lower than that of the transmission line, other considerations point to one or another of several standard voltages. Standard generator voltages are 240, 480, 600, and 2300 volts. 6600-volt machines are usually con-

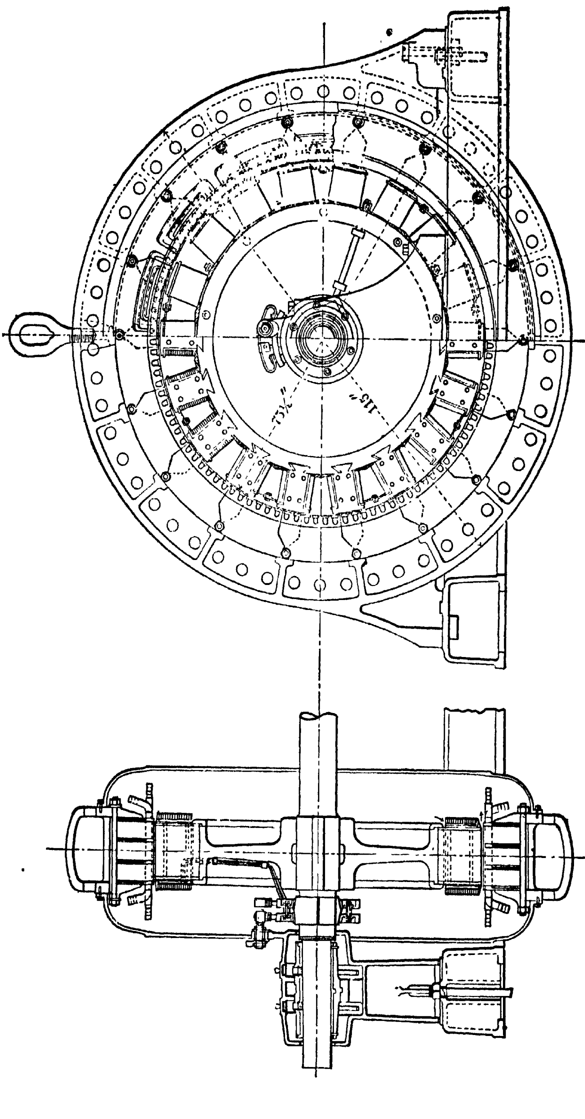

FIG. 4.—Three-phase, revolving field generator.

sidered semi-standard since the full machine rating can not be obtained. With low voltage, such as 480 volts, the current to be handled for any considerable amount of generator capacity would necessitate large and expensive cable connections from the generator to the switchboard as well as expensive high-capacity switching apparatus. On the other hand, high voltage will necessitate extra expense for insulation and switching apparatus for higher voltage. It is always a compromise between high voltage and large current capacity and must be decided individually in each case. In general, voltages above 6600 should be produced by transformers.

It must be understood that there is a distinction between "generator capacity" and "power." The reason for this is that the generator must be made large enough to deliver both the rated voltage and current, whereas, the power is the product of these two and the power factor. Generators are, therefore, rated in kilovolt-amperes (kv.a.), not in kilowatts (kw.). The power factor is also usually stated, since it requires a more liberally designed machine to deliver a given kv.a. at a lower power factor. The power factor is determined by the nature of the load and by the electrical constants of the transmission line. When the load is largely from synchronous motors, the power factor may be kept at any desired value. When the load is principally supplied to induction motors, the power factor of the load is less than unity, unless some correction is made by the use of synchronous condensers (see Chap. X). The power factor of induction motors will vary with their size and speed. A large, high-speed induction motor may have a power factor as high as 92 to 95 per cent., whereas a small, low-speed machine may have a power factor as low as 50 or 60 per cent. For example, a 60-cycle induction motor rated at 300 hp., running at 100 r.p.m., will have a power factor of not more than 40 per cent. A machine of 1000 hp., running at a speed of 514 r.p.m., would have a power factor of, perhaps, 96 per cent. For the same horsepower and speed, 25-cycle induction motors have better power factors than those for 60 cycles.

Since most of the transmission-line systems are three-phase, most of the generators are likewise three-phase. As explained elsewhere, three-phase distribution is most economical of copper.

Of all the high-voltage transmission systems of any size, more than half operate at 60 cycles. In this country there are

a few at 50 cycles, and some at 25 cycles and odd frequencies. The factors which determine the choice of frequency are:

(*a*) Cost.
(*b*) Service.
(*c*) Water wheel.
(*d*) Regulation of transmission line.
(*e*) Natural frequency of transmission line.

Owing to the interdependence of all of these factors, the order in which they are placed must not be taken as an indication of the order of importance. What is the determining factor for one system may be of no importance in a second case.

The cost of 60-cycle generators is usually slightly lower than that of 25-cycle generators for the same output and speed. The cost of transformers is, also, considerably lower for the higher frequency.

The use to which power is put is not now so important a factor as it has been in the past. For lighting, any frequency below 30 cycles is not satisfactory, since the flicker in the light at lower frequency is noticeable to the eye; 50 and 60 cycles are the predominating frequencies where lighting is a large part of the load. When the service demands direct current, and rotary converters are used for the change from alternating to direct current, 25 cycles is slightly better, but 60-cycle rotary converters are now extensively used.

The operating speed of a water wheel is determined, within a limited range, by the head and capacity and the frequency is at times, limited by the wheel speed. This was, no doubt, the predominating factor in the selection of 25 cycles for the Keokuk plant. The low head of 32 ft. and the large units, 10,000 hp., made necessary a very low speed, namely 57.7 r.p.m. If 60 cycles had been chosen, the generators would have had 124 poles, necessitating an extremely large diameter for this rating. Where vertical units are used, large diameter of generator rotor necessitates excessive cost for bearings and extra strength of rotor spider to carry the weight of the poles at the great radius. A moderate or high head plant is better adapted to 60-cycle generators, since the higher speed of the water wheels might make 25-cycle generators impossible because of the small number of poles, small diameter, and great length.

The voltage regulation of the transmission line is not an important factor. While the regulation of a 25-cycle line is

better than that of a 60-cycle line, it is a rare case when close regulation is an essential feature of a transmission line, particularly if the capacity is large. By the use of voltage regulators at the power house, or synchronous condensers at the receiving end, it is possible to maintain normal voltage at the receiving end of the line very closely, over any range of load. If very fine regulation is necessary, as for lighting, it is usually better practice to install a motor-generator set of small capacity for this load alone and use direct current with a short line and automatic regulators at the generator. Another alternative is the use of feeder voltage regulators which may be installed locally at the point where good voltage regulation is necessary.

The frequency selected should not be of such a value that any of the higher harmonics of importance will give resonance with the natural frequency of the line. (See Chap. XX.)

The runaway speed of a water wheel is nearly double the normal speed. All generators which are driven by water-wheels should, therefore, be mechanically strong enough to momentarily withstand twice normal speed. This is a safeguard in case the water-wheel governors should fail. Runaway speeds are nearly always attained when the governors are being adjusted for the first time.

The cross-section of the copper in the coils of the generator is determined by the current which has to be carried. About 1500 to 2500 amp. per square inch are allowable, depending on the cooling facilities of the machine. The flux densities in the teeth of the core should not be over 100,000 lines per square inch, and in the core, back of the slots, it should not exceed 70,000 lines per square inch. These values are for 60-cycle generators; 25-cycle generators usually have densities slightly above these values.

Ample space should be provided for proper ventilation. The windage of the rotor is usually sufficient for cooling purposes, but, where desirable, fans may be added to the rotor to improve the ventilation. The core is usually divided into a number of sections with radial air spaces between adjacent sections, the width of each section not exceeding 3 to 4 in. The air passes through these ducts, cooling both the coils and the core. The coil ends are cooled by properly directing the air against them by means of the end shields. In case the machines are very long, measured axially, forced ventilation is resorted to.

In this event, the machine is fully enclosed, and the air is forced through the proper channels by fans.

As indicated in the last paragraph, the losses of the generator manifest themselves in the form of heat. In the coupled type of machine, where the bearings are furnished by the generator manufacturer, the losses taken into consideration in the statement of guarantees for efficiency are:

(*a*) Friction of the bearings and windage.

(*b*) Core loss.

(*c*) Copper loss of both stator and rotor.

In certain cases, stray load losses are also included. These losses are due to distortion of the flux paths, increasing the core loss, and the resulting unequal distribution of the current in the conductors increases the stator copper loss.

Testing.—Since all testing is most readily done at the manufacturer's plant, it will be assumed that the facilities there existing, are obtainable. The various losses are determined as follows: The windage and bearing friction may be determined by driving the machine by a motor whose losses are known. The input to the motor, corrected for its losses, is then the loss of the machine under test. A compromise, which is frequently adopted for alternating-current generators, is to run the machine as a synchronous motor carrying no external load. The input to the motor, corrected for the no-load core loss at the test voltage, is a close measure of the windage and bearing friction. The machine must be excited to such a degree that it will draw a current at 100 per cent. power factor.

The core loss is determined in a manner similar to that used for windage and friction and may be made a part of that test. In determining the windage and bearing friction, the field of the generator is unexcited, whereas to determine its core loss the field is excited to such a value as to obtain a voltage equal to the rated voltage of the machine at the generator terminals. This is not a true method of determining the core loss under load but, inasmuch as there is no satisfactory method of finding the exact loss, this is adopted as a sufficiently accurate substitute.

The copper losses of both the stator and rotor are determined from the measured resistance of the windings and the current they are each to carry. Due correction must be made for the rise in temperature during actual operation. It is generally, roughly assumed that the resistance will be about 15 per cent.

greater than the resistance at 25°C. (the usual air temperature upon which guarantees are based). This allows a rise of 40°C. The field current is regulated by a resistance. The losses in this rheostat are sometimes included but not usually. In case they are included, the rotor copper loss should be computed as the product of the nominal excitation voltage and the rotor current.

The stray load losses are measured with the same apparatus as is used for the determination of core loss. The stator is short-circuited and the rotor is excited to give full-load current in the short-circuited stator windings. The input to the driving motor is found and corrected for the motor losses. The input to the machine under test is made up of the stator copper loss and the stray load losses. By deducting from this quantity the copper loss, figured from the measured resistances, the stray load losses are obtained. Of course, the windage and bearing friction must be also deducted.

Knowing the losses which are to be included in the computation of efficiency, the efficiency is found as the ratio of the rated output of the machine, in kilowatts, to this output plus the losses. The field current required for full load may be found from the saturation curves of the machine, which are explained in the succeeding paragraph.

In addition to efficiency guarantees, manufacturers also state the regulation and the temperature rise. Inasmuch as the regulation is dependent on the power factor of the load, the power factor is always stated when giving regulation guarantees. The regulation may be found from the results of three tests, namely, the open-circuit saturation curve, the short-circuit saturation curve, and the full-load, zero power-factor curve. The short-circuit saturation curve is not necessary, but serves to define the zero power-factor curve, when taken as explained here. The open-circuit saturation curve is usually taken at the same time that core loss is found. Tests are made of the machine running at normal speed and with varying degrees of field excitation. The corresponding voltage for each amount of excitation is measured. A curve is then plotted with terminal voltages as ordinates, and field currents as absicssæ, as in Fig. 5. The short-circuit saturation curve is obtained at the same time that the stray losses are determined. The results are plotted with short-circuit stator current as ordinates and field current as

abscissæ, as in Fig. 5. The zero power-factor saturation curve may be very closely obtained by running the machine as an over-excited synchronous motor, drawing full-load current with no mechanical output. This test is made by applying different voltages to the stator terminals and adjusting the field current for each voltage applied so that full-load current is drawn by the stator. From the readings a curve is plotted, with voltages as ordinates and field currents as abscissæ. This test should not be extended below half voltage because the windage and bearing friction will raise the power factor at low voltage. The beginning of the zero power factor curve is found as the value of field

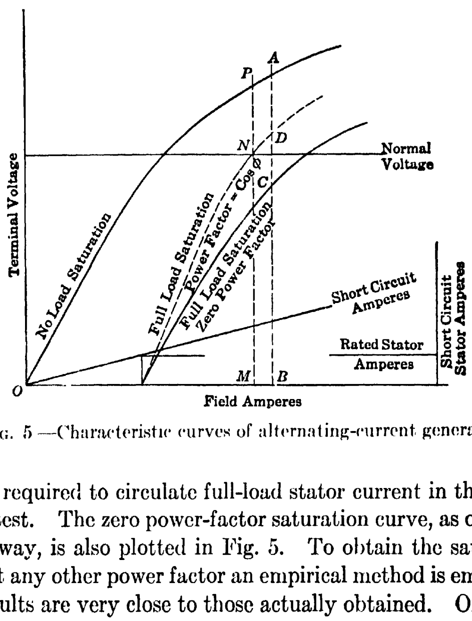

FIG. 5.—Characteristic curves of alternating-current generator.

current required to circulate full-load stator current in the short-circuit test. The zero power-factor saturation curve, as obtained in this way, is also plotted in Fig. 5. To obtain the saturation curve at any other power factor an empirical method is employed. The results are very close to those actually obtained. On a base line EF, Fig. 6, lay off a distance EC equal to the IR drop in the stator windings at full-load current, to the same scale as used for the saturation curves. Draw the line CB at such an angle, ϕ, with the base line that cos ϕ is the power factor desired. From E draw a perpendicular to the base line of such length that EA shall equal the internal drop from no-load to full-load zero

power factor. (This value is the distance *CA* on the saturation curve, Fig. 5.) From *A* as a center swing an arc with radius equal to the open-circuit voltage *AB*. The distance *CB*, to scale, will be the voltage of the machine at the specified power factor and is plotted on the saturation curve as *DB*. This process is to be repeated for several values of field current until sufficient points have been obtained to draw a curve. The point at which this power-factor saturation curve cuts the normal voltage will give the field current necessary to carry full load at the specified power factor. In most machines the *IR* drop is negligible, except at power factors above 90 per cent. Below 90 per cent. power factor the distance *EC* may be neglected.

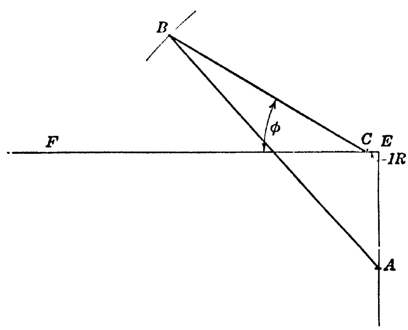

FIG. 6.—Graphical computation of generator saturation curve.

The regulation of the machine is defined as being the ratio of the rise in voltage, when full load is thrown off, to the normal voltage, and, in the saturation curve, is found to be the ratio of *NP* to *MN*. It will now be readily seen that the lower the power factor the worse the regulation becomes.

The temperature rise is measured by thermometers. On all stationary parts, such as the core and stator windings, thermometers may be placed and observed during the progress of the heating test. When these thermometers have attained a constant temperature it may be assumed that the whole machine has reached its ultimate temperature. The machine is then shut down, and thermometers are placed on such parts of the revolving element as may be desirable, such as the field coils and collector rings. It will be found that the thermometers on the stationary member will rise slightly after shutdown, even though they have

been constant before that time. The highest recorded temperature, either running or immediately upon shutdown, is to be considered the actual temperature of the machine. The temperature rise may be found as the difference between the maximum thermometer reading on the machine and the average of several thermometers used to record the temperature of the surrounding air. In the case of fully enclosed machines, holes are sometimes drilled in the frame to permit the placing of thermometers. The temperature rise should, in this case, be taken above the temperature of the air entering the air inlets. The usual guarantee given on alternating-current generators is 40°C. rise above surrounding air for both the stator and rotor at full-load kv.a. and at 80 per cent. power factor for continuous operation. On 25 per cent. overload for 2 hr., immediately following continuous full-load operation, a temperature rise of 55°C. on the stator and rotor is usual for 80 per cent. power-factor operation. At unity power factor (100 per cent.) the stator temperatures will be the same because the actual current delivered is the same, but the rotor will be from 5°C. to 10°C. cooler because less field exciting current is required to maintain the voltage in the latter case, than in the former. On the basis of a room temperature of 25°C., the actual temperature at the end of the overload heat test will be not higher than 80°C. (176°F.). For the usual types of insulation this allows a margin of about 15°C. below the maximum allowable temperature which the insulation will withstand without injury. It will be evident that it is impossible to measure the temperature at the hottest part of the machine. If the margin of 15°C. is adhered to, it may be safely assumed that no part of the machine will be above 95°C. If the generator is to operate in a climate where the room-temperature is likely to be greater than 25°C., it is good practice to specify generators with a temperature rise of 35°C. on continuous full load.

There is a tendency among engineers to call for what is termed a "maximum rating" of generators. This rating is the maximum continuous load which the generator will deliver with a temperature rise of 50°C., no allowance being made for any overload capacity. This "maximum rating" has not yet been universally adopted.

The present tendency is to call for machines with poor regulation. The short-circuit current of such a generator is lower

than that of a machine with good regulation. Hence, if a short-circuit should occur on the line, the excess current drawn from a machine having poor regulation, would be less than that from one having good regulation, and the former machine would be less liable to damage. In order to further limit the rush of current on short-circuit, external "current-limiting reactances" are sometimes used. At present, the regulation guarantees usually given, are around 10 per cent. at unity power-factor load and 20 per cent. at 80 per cent. power-factor load.

All windings are tested for dielectric strength at the works of the manufacturer. Stator windings are tested between the winding and the core at a voltage equal to twice the rated terminal voltage, plus 1000 volts. Thus, a 2200-volt generator should be tested at 5400 volts. The field windings of a generator are usually tested at 1500 volts to ground, regardless of the excitation voltage, although the A. I. E. E. rules require ten times excitation voltage. If the machine is to be used as a synchronous motor and is to be started with the field winding short circuited, the test voltage is the same as when used as a generator. When started with the fields open-circuited, the usual test voltage is 5000 volts for an excitation voltage not in excess of 250 volts. These test voltages are never to be applied by slowly raising the voltage to the required value, but by switching the test voltage from normal operating voltage to the maximum test voltage, then holding it at that point for a period of one minute and then reducing it to normal. Such tests are not approved by manufacturers, but since any surges that may come on the machine windings in practice are suddenly applied, a high-voltage test should be applied in the same way.

Exciters.—Small direct-current generators, called exciters, furnish energy to the fields of the large generators. As mentioned before, the voltage of the exciters is usually 125 volts and sometimes 250 volts. There are four general methods by which the exciters are driven. These are:

(*a*) Belted to the generator (see Fig. 7).
(*b*) Direct-connected to the generator (see Fig. 8).
(*c*) Driven by an auxiliary water wheel.
(*d*) Driven by an alternating-current motor.

The first method is the most frequently used for small units. The exciter is usually made large enough to supply energy to two alternators. In case of breakdown, temporary wiring may be

installed so that the exciter of some other machine can supply current to the one having the disabled exciter, one exciter supply-

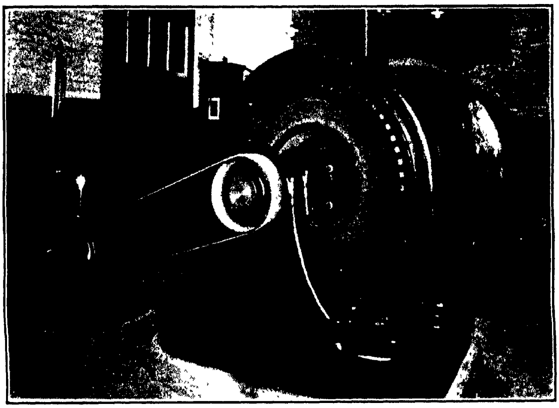

FIG. 7.—Generator with belted exciter.

ing then two generators. The speed of the exciter, when belt-driven, may be higher than that of the main generator, so that the

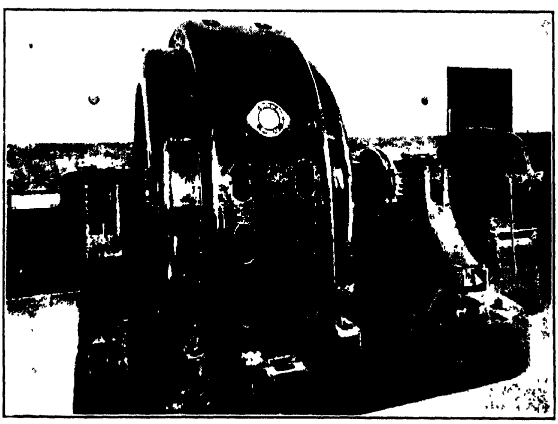

FIG. 8.—Generator with direct-connected exciter.

exciter may be comparatively small. A belt-driven exciter is, therefore, smaller than one of the same capacity directly con-

nected to the shaft of the generator. The belted exciter may take valuable space in a power house and can not be used where the building space is limited. In spite of the larger size of the direct-connected exciter, it takes up less room, since it is mounted on a short extension of the base, or on a bracket. The space for the belt is thus eliminated. The cost of the larger machine may be excessive, unless the speed of the generator is sufficiently high to make possible a reasonable design. The direct-connected exciter is best adapted to large generators where considerable exciting energy is required. There is one objection to both of these methods of driving exciters which may become serious under conditions of badly fluctuating load on the generator. The speed of the exciter is directly dependent upon the speed of the generator to which it is connected. Under variable load, the speed of the generator will vary above or below normal, for short instants, while the water-wheel governor is acting to take care of the change in load. Suppose, for example, that a generator is carrying a load near normal. A large part of this load is suddenly dropped off. The water wheel and generator tend to speed up before the water supply can be cut down. The speed of the exciter also, increases. The voltage of the generator is directly proportional to the speed, as is also the voltage of the exciter. When the voltage of the exciter rises, the generator excitation is also increased, and, consequently, the voltage of the generator increases doubly with speed change. The effect is thus cumulative. Unless some form of automatic voltage regulator is used, this abnormal rise of voltage may cause trouble to the users of power on the transmission line.

The fourth method of drive, namely, by motor, is also open to this objection since alternating-current motors run at a speed which is proportional to the speed of the generator.

In order to eliminate this trouble, in part at least, the exciter may be driven by an auxiliary water wheel. Water wheels in such small sizes as are necessary for excitation purposes (only a few per cent. of the rating of the generator) are usually inefficient. Where the loss of water is serious, this method is not to be recommended.

In order to derive the benefit of a direct-connected exciter from the standpoint of space economy and, at the same time, to use a small exciter run at a comparatively high speed, motor-driven exciters are used. A further benefit may be derived from

the use of a synchronous motor to drive the exciter. This motor can be used to raise the power factor of the generators in the same way that a synchronous condenser may be used at the receiving end of the line. If this method is the one adopted, it is necessary to supply at least one exciter driven by one of the other three methods. Since the motor takes energy from the generator, and the generator can not deliver energy until the fields are excited, a separate exciter must be used to start the plant. This is usually a small machine belted to one of the generators, or a small water-wheel driven set, capable of supplying excitation to one generator for a short time only. In such an

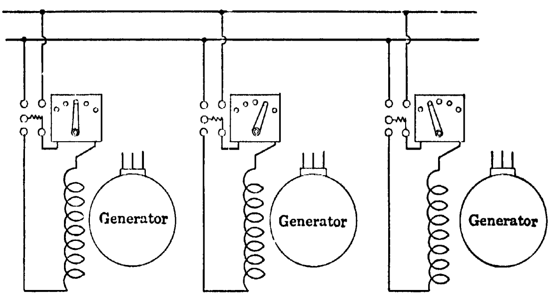

FIG. 9.—Connections for generator fields supplied from single exciter circuit.

installation the method of starting is as follows. One of the main generators and the small auxiliary exciter are started. The field of this generator is excited from the auxiliary exciter which has been connected to the exciting mains or busbars. The motor-driven exciters are then started and the exciters themselves connected in parallel with the auxiliary. The auxiliary may then be disconnected from the exciting circuit and shut down.

In some cases, storage batteries are used instead of a water-wheel auxiliary. The batteries are charged slowly from the regular exciters to prepare them for the next time when a start is necessary. The storage batteries may be used as an emergency source of excitation in case of breakdown of one or more exciters.

A simple diagram of connections for use when several generators are to be excited in parallel from a common exciting busbar is shown in Fig. 9. Belt-driven and direct-connected exciters are usually not so operated. Each one is connected

permanently to its own generator field only, and regulation is obtained by use of the exciter-field regulator instead of by generator-field regulator, which latter may be omitted. This method saves losses in the generator field regulator, which are much larger than the losses in the exciter-field regulator, and a further saving will be made in the switchboard. If desirable, connections may be made to exciting busbars to provide interconnection of exciters, should one exciter break down.

CHAPTER II

TRANSFORMERS

General.—Since it is impracticable to generate very high potentials in a revolving machine—13,000 volts being the highest known in practice—it is necessary to use transformers to raise the generated voltage to a pressure at which it is economical to transmit the energy. Since transformers have no moving parts, the conductors may be readily insulated for any desired voltage. Transformers are now in successful operation for pressures as high as 150,000 volts.

The essential parts of a transformer consist of a steel core, and coils of insulated copper wire, or strip, encircling the vertical legs of the core, as shown in Fig. 10. The core is built up of thin steel laminations, bolted together. The bolts are insulated from the laminations so that eddy currents may not pass over them from the laminations. Owing to stray magnetic fields, small voltages are induced in the steel core which cause large currents to flow in a solid piece of steel. These currents are materially reduced by laminating the core, thereby reducing the losses in the core.

The windings consist of two elements, a primary and a secondary, well insulated from each other. The voltage of the generators is impressed upon the one, while the other is connected to the transmission line. The ratio of the primary to the secondary voltages is the same as the ratio of the number of turns connected in series in the primary winding to the number of turns connected in series in the secondary winding.

The transformer is usually placed in a steel tank filled with oil in which the core and the windings are submerged. The connections are made to the windings through insulating bushings or terminals extending through the cover.

Transformers may be of two types, shell and core, and each type divided into four general classes:

1. Oil-insulated, self-cooled.
2. Oil-insulated, water-cooled.

3. Oil-insulated, self-cooled with external radiators.
4. Air-insulated, air-cooled (called air-blast type).

Core and Shell Types.—The difference between the shell and core types may be most easily understood by referring to Figs. 10 and 11. Here it is seen that the core type consists of one

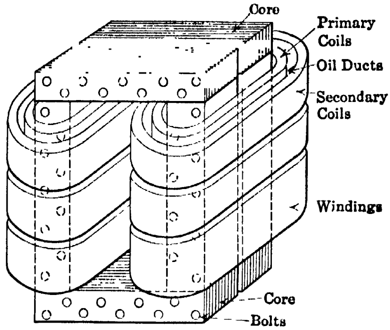

Fig. 10.—Core-type transformer.

magnetic circuit, or link, and two electric circuits, or links. The shell type, on the other hand, consists of two magnetic circuits and one electric circuit. There is a variation of the shell type which is called the cruciform type. This consists of four magnetic circuits and one electric circuit. This last type is slightly

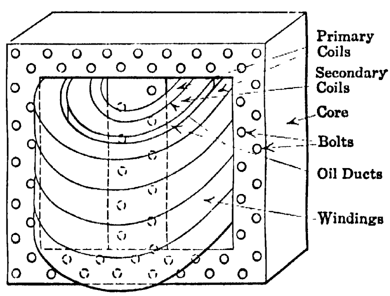

Fig. 11.—Shell-type transformer.

more economical of steel than the other two kinds because the mean length of path of the magnetic circuit is somewhat less than that of the usual shell type of the same capacity. The manufacturing costs are, however, slightly greater, practically offsetting the saving of material. There is very little actual

difference in cost between any of the three types. A further characteristic may be noted. The core-type construction has a long length of path in the steel and a short path in the winding. The shell type is the reverse, having short iron paths and a long mean length of turn of the coils. The former is what might be termed an iron transformer, the latter a copper transformer. The tendency would naturally be to have the greater losses in that material which predominates, but the proportions may be altered to give any desired division of losses.

For small, low-voltage (6600 volts or below) distributing transformers, in capacities up to 50 or 100 kv.a., the shell type, or cruciform type, is desirable. Some manufacturing concerns make both shell and core types, supplying either as requested. There is very little choice between them, there being, perhaps, slight differences in cost, losses, and floor space. For power transformers, the core type is gradually replacing the shell type, except in the case of air-blast transformers. In this latter instance it is much more simple to use the shell type, as air cooling of transformers would be rather difficult with the core-type construction. The core-type construction is desirable for power transformers because it can be more readily and rapidly repaired. The shell-type transformer is usually made so that the core consists of but two pieces, the center leg and the outside yoke. In order to repair a damaged coil it is necessary to dismantle the core, a job which is best handled at the manufacturer's plant where special tools are available for such work. In small sizes this feature is not of much importance because of ease of transportation to the repair shop. The core-type construction is made with the core in four pieces, the two vertical legs and the two horizontal yokes. To remove the coils it is only necessary to take off the top yoke. This is usually held on with long studs, extending from channel irons below the lower yoke to similar channel irons above the upper yoke.

For high voltages the core type is usually preferred. Since the winding is divided into two sections, one on either leg, the number of coils may be made greater for a given height of transformer without reducing the size of a single coil to such a dimension as will make it mechanically weak. The number of coils is fixed, within limits, by the voltage, it being usual to allow 1500 to 3000 volts per section. A further consideration, which, however, is more apt to influence the size of conductor

used, limits the voltage between adjacent conductors to less than 500 volts, these values being approximate. In many instances it might be advisable to exceed these values, the insulation being graded accordingly.

Oil Insulation.—A small percentage of the transformers in use is air-insulated, but for voltages in excess of 33,000 all transformers are oil-insulated. The tank is entirely filled with a good insulating oil and the transformer is immersed in it. The oil circulates freely over the core and through the windings. There should be provided ample oil ducts between the different parts of the windings in order to insure free circulation of oil. Since the oil serves as an insulator as well as a cooling medium, the clearances between windings is further influenced by the voltage, this usually being the determining factor.

Oil-insulated transformers, in sizes up to about 500 kv.a., may be self-cooled. The tanks are made of corrugated sheet steel. The corrugations give increased radiating surface, thus giving better cooling facilities than a smooth tank. The heat generated in the core and windings of the transformer is conducted away from them by the oil, the oil in turn being cooled by contact with the walls of the tank. The oil circulates naturally, due to the difference in density of the hot oil near the windings and the cooler oil near the tank walls. The transformers must be so located that air may freely circulate over the outside tank surface. Special attention should be given to the ventilation of buildings in which transformers are to be installed. A revolving machine will produce its own air circulation by windage of the revolving element, whereas a transformer is cooled by radiation and convection only.

Water Cooling.—When the capacity is above 500 kv.a., some external method of cooling must be used. If water is available, this may be used for the purpose. Coils of water pipe are immersed in the top of the oil, and cold water, which absorbs the heat from the adjacent hot oil, is forced through the pipe. The warm water is usually discarded. Before the adoption of the external radiator type of transformer, when water could not be unnecessarily wasted, the warm water was frequently cooled in a manner similar to that used for cooling the condenser water in a steam plant. The cooling coils are made of seamless wrought iron, except in such cases where the water, because of its chemical contents, is liable to cause corrosion. Seamless copper or brass

tube is then used. All piping must be absolutely water-tight, since a very small percentage of water in transformer oil will cause the oil to lose its insulating properties. Such piping is usually tested at 250 lb. per square inch, hydraulic pressure.

Several methods are employed in order that attendants may note whether water is flowing through the cooling coils. In one, the water coming from the transformer is emptied into a discharge basin, the outlets from the transformer being cut off a short distance above the basin. When water is flowing, the stream is visible as it falls into the basin. Another arrangement is that of an alarm bell which rings when the water supply is cut off. The apparatus is very simple and is shown diagram-

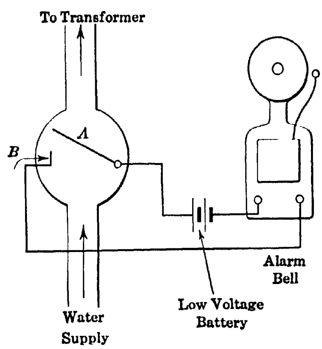

FIG. 12.—Cooling-water alarm.

matically in Fig. 12. A flap valve *A* is held up against gravity by the flowing water. As soon as the water supply is cut off, the flap drops onto an insulated contact button *B*, closing a low-voltage circuit through a battery and a gong, or other alarm signal.

Impurities in cooling water will tend to form a hard scale on the inside surfaces of the cooling coils. In time this scale will become thick enough to seriously interfere with the heat transfer from the hot oil to the water. If it should be noticed that a water-cooled transformer is running hotter than it should, and the supply of water is normal, the pipes should be cleaned. A chemical examination of the scale or water will indicate the remedy. A weak solution of a reagent which will attack the scale should be run into the coils and allowed to stand for a

time, though not long enough to injure the pipes. It should then be flushed out. If serious trouble is to be expected in this respect, water-cooled apparatus is not to be recommended unless the cost of water purification is low. At the present time, self-cooled transformers can be purchased for any desired rating and, while more expensive than the water-cooled for the same capacity, may be enough cheaper in upkeep to warrant the additional investment.

The amount of water to be used in water-cooled apparatus is dependent solely on the losses in the transformer. It is usual to allow about 1/3 gal. per minute, per kilowatt loss. Thus, a 1000-kv.a. transformer with a full-load efficiency of 98 per cent. will require about 6½ gal. of water per minute, since the loss is 2 per cent. of the rating, or 20 kw. Since 1 kw. will raise the temperature of 3.8 gal. of water 1°C. per minute, the above rule considers a difference in temperature between incoming and outgoing water of approximately 11.4°C.

When water is not plentiful and can not be spared for cooling purposes, the external-radiator type of transformer is used. The transformer and tank are the same as for the water-cooled type, except that the cooling coils are omitted. Radiators are mounted external to the tank, in another room if desirable, and connected to the transformer tank by piping. The arrangement must be such that the difference in density of the cooler and hot oil will cause the oil to flow down the radiators, into the tank at the bottom, up through the windings, and into the top of the radiators. The radiators are made of pressed steel similar to those used for heating buildings.

Air Cooling.—In distributing substations, particularly where the maximum voltage is 33,000 volts or below, air cooled transformers may be used if conditions make them preferable. The bottoms and tops of the tanks, or more properly, cases, are open. The case is placed over an opening in the floor which connects with a supply of air furnished by a blower at a pressure of from 1 in. to 2 in. of mercury. The air is forced into the bottom of the case, up through the windings, and out of the top of the case. The substation must be arranged so that this warm air may freely circulate and leave at the top of the building. In winter, of course, the warm air may be used to heat the substation. Air which is to be forced through transformers must be thoroughly cleaned, washed and dried in order that

no particles of foreign matter may get into the windings and cause breakdown. The amount of air required is determined in the same way as water supply for the water-cooled transformer. About 150 cu. ft. of air per minute is usually allowed per kilowatt loss on the basis of atmospheric pressure. This is figured from the heat capacity of air in the same way as for water cooling. 1 kw. will raise the temperature of 1650 cu. ft. of air, at atmospheric pressure, 1°C. per minute. For the example in the paragraph under water-cooled apparatus it would be necessary to allow about 3000 cu. ft. of air per minute, and the temperature rise of the air in passing through the transformer would be about 11°C.

Coils.—Transformer coils are made in a variety of ways. Small transformers usually have both the primary and secondary coils wound together, concentrically. On a winding form of the proper shape, a layer of insulation is first placed. This may be heavy pressboard or micarta. Since this first layer is to be next to the iron core, it must be heavy enough to withstand abrasion as it is slipped over the core. In the use of micarta, or other formed insulation, the material must be moulded to shape in its manufacture, since it is a rigid solid tube. Between each two layers of the winding a layer of thin pressboard or horn fiber is placed, its thickness depending on the maximum voltage difference between any two conductors of the two adjacent layers. This layer insulation is usually shaped as shown in Fig. 13. This method gives insulation on the ends of the coil. The first layer of the winding is started on such a piece of folded fibrous material. In small transformers of comparatively low voltages, insulation between adjacent turns may consist of a double cotton covering on the wire, or an enamel insulation with one cotton covering. End turns, or the turns which will be connected to the transmission line from which voltage surges may come, are usually extra insulated by placing a cord or other insulating material between them. Windings made of strip copper may be insulated between turns with a wrapping on the conductors of linen tape or other fibrous insulation. The folded ends of the layer insulation are designed to take up the same thickness as the wire, so that the coil will build up to the same thickness throughout. In small distributing transformers where

FIG. 13.—Layer insulation.

the low-tension voltage is not more than 550 volts, it is usual to wind half the low-tension winding first. Insulation, consisting of combinations of the insulations before mentioned with mica and varnished cambric, is then wound around this portion of the coil, the amount depending on the test which is to be applied in order to prove the insulation between high- and low-tension windings. The high-tension coil is then wound on. Insulation is applied in the same way as for the high-tension coil. The remainder of the low-tension coil is next wound on. Outside of this is a layer of thin fibrous material held on by a wrapping of cotton tape. The procedure here outlined is not used for voltages much above 2200 volts. If the transformer is of the shell type, one such coil is used; if of the core type, two such coils. For small sizes, where the completed transformer core and coils can be put into so-called "compounding tanks," the next step is to assemble the core and coils. The transformer is then further insulated by what is called "vacuum impregnation." It is placed in a compounding tank and the air drawn off by means of a vacuum pump, a high vacuum being maintained for a few hours. At the same time the tank is heated in order to drive off any moisture present. This removes all the air and moisture from the coils. Air is a poor conductor of heat, and, in order to improve the heat conduction from the center of the coil to its outside surface, the air is removed, and the crevices are afterwards filled up with an insulating compound. At ordinary temperatures, this compound is solid, but at a temperature of approximately 95°C. (200°F.) it becomes soft, and at a slightly higher temperature it is fluid. The transition from solid to fluid is gradual. The compound is heated to about 110°C. (230°F.) and pumped into the compounding tank which is surrounded with steam coils to keep the compound fluid while it is finding its way into the transformer coils. After 4 hours or more the compound is drawn back into the storage tank and the transformers are allowed to drain off surplus compound. The transformers are then ready for assembly. The leads are attached, the superstructure and terminal boards are added and the transformer is placed in its tank. The tank is filled with oil and the transformer is ready for testing. The compound must be oil-resisting since it is to be placed in an oil-filled receptacle.

For transformers which are too large for the compounding

tanks, the coils are impregnated alone before assembly on the core. Wooden frames are built around the coils so that the surfaces which are to fit snugly against other parts may not be heavily coated with compound. These forms retain the coils in the proper shape, when heating tends to distort them. The coils are then assembled on the core and completed as described.

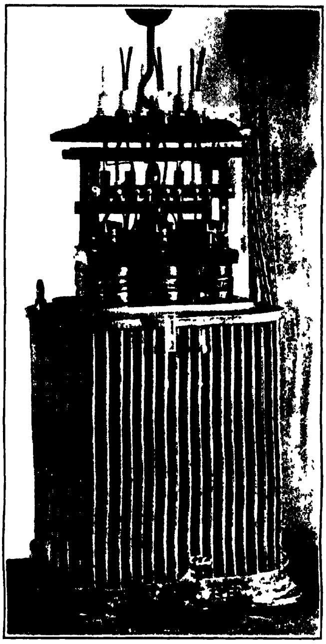

FIG. 14.—Core-type transformer partially removed from case.

High-voltage coils are built up in sections. As stated, the voltage largely determines the number of sections. Each separate section is wound and compounded in a manner similar to that before outlined. They are then assembled as shown in Fig. 14. It will be noticed that there is a small space allowed between adjacent coils. Small wooden or fibrous blocks are put in to separate the coils, which separation provides both an insulating space and an oil duct for cooling purposes.

Small lighting transformers have the low-tension winding in two parts, and between these two parts is placed the high-tension winding. The purpose of this is to improve regulation. This is possible only for comparatively low voltages, not much above 6600 volts maximum. For higher voltages, the low tension is first wound on complete and the high-tension winding is put outside, in sections. The regulation of this arrangement is not so good as that of the former.

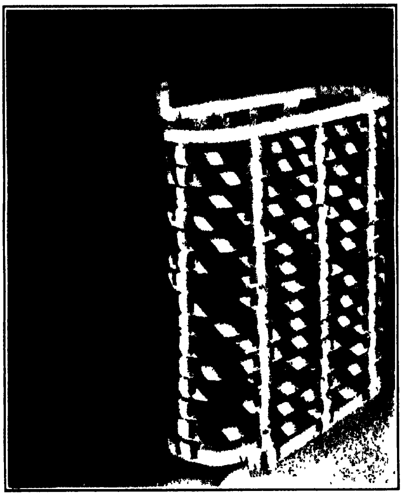

FIG. 15.—Transformer coil. Low tension; space insulation.

Power transformers are at present designed for high reactance in order to limit the inrush of current on short-circuit. This point is discussed in the chapter on "Generators." It is due to the arrangement of coils that the regulation of high-voltage apparatus is not so good as low-voltage apparatus of the same capacity.

For voltages between 2200 and 6600, when the high-tension coil is between two sections of the low tension, it is usual to wind the high tension in sections in a way similar to that used for higher-voltage transformers except that the sections are not spaced apart, but wound close together, and separated only by the folded paper used as layer insulation.

When the low-tension voltage of larger transformers is low enough for the turns of the coil to be formed into a single-layer winding, the coils are sometimes wound as shown in Fig. 15. The copper strips are not insulated at all, but have a wrapping of tape to hold together several conductors in parallel, and each turn is separated from the next by several blocks of some insulating material. This type of coil has excellent cooling facilities. All sides of every turn are directly exposed to the cooling medium and are not covered up with insulation, which is not as good a heat conductor as the metal. This coil is also economical from the standpoint of both labor and material, for the same effective heating The cooling medium is depended on for insulation between turns.

The air-cooled transformer has a distinctive type of coil construction. The transformer is usually assembled in such a way that the core forms a part of the case. The air passes up through the coils and "windows" of the core. The coils are the kind known as "pancake" coils, the name originating from its flat shape. The spacing between coils must be ample for both cooling and insulation.

Current and Flux Densities.—A few notes on general design may be of interest. The copper cross-section necessary for a conductor is determined by the current it is to carry. The current density will vary with the type of construction, the cooling facilities being the determining factor. Water-cooled transformers have current densities of from 1500 to 1400 amp. per square inch; self-cooled transformers from 1300 to 1200 amp. per square inch, and air-cooled, from 1000 to 900 amp. per square inch. These values will vary with the particular design and are approximate only. Many designs are outside of these limits. The losses in each winding are equal to the effective resistance of that winding multiplied by the square of the current flowing in the winding, or I^2R.

The flux density used in the core will depend on the frequency and, hence, on the core loss and the exciting current. For 60-cycle apparatus the core loss, and consequent heating, is the factor which limits the flux density to not more than 90,000 lines per square inch. For 25-cycle apparatus a higher density is permissible. For the same flux density the core loss is lower for 25 cycles than for 60 cycles, the iron loss being proportional to the frequency. The exciting current, however, does not vary

with the frequency. This is the limiting factor for 25-cycle transformers. The exciting current should not exceed 10 or 15 per cent. of the rated full-load current. In order to limit the exciting current, the flux density is not allowed to go above 100,000 lines per square inch for 25-cycle transformers. All of the foregoing figures are averages for the usual rational designs of power transformers.

The best grades of silicon steel are used for 60-cycle transformers. The chief reason for its use is low core loss. 25-cycle apparatus does not need as good a quality of steel as 60-cycle apparatus, principally because the core loss is not as large for the same flux density. In some cases carbon steel is used for 25-cycle transformers. The thickness of the steel laminations will vary from 0.010 in. to 0.025 in., depending on the allowable core loss. Core loss is made up of two distinct parts, one due to hysteresis loss and the other due to eddy currents in the steel. The hysteresis loss per unit volume of steel varies directly with the frequency and with the 1.6 power of the maximum flux density. The eddy-current loss varies directly with the square of each of the following: lamination, thickness, frequency, and maximum flux density. It is generally, roughly assumed that the total core loss varies with the 1.8 power of the maximum flux density and with the 1.4 power of the frequency, these values including all the losses mentioned. Designers use exact figures from curves plotted from tests of samples of the particular kind of steel they expect to use. All of the steels now used are "non-ageing," that is, the core loss does not increase with time.

Mechanical Details.—Clearance distances between windings, and between windings and core, are determined, almost solely, by insulation requirements. Oil ducts in oil-filled transformers are never smaller than about ¼ in. measured in any direction. There must be ample clearance from all parts of the transformer to the tank in order to provide for proper oil circulation. This clearance should not be less than 3 to 4 in. The quantity of oil is determined by the tank size. Enough oil is allowed to cover the terminal boards by at least 2 in., and more for high voltages. Assuming that the manufacturer has a standard tank which will just allow a given transformer to go in with the proper side clearances, the height of the tank is determined by the total losses of the transformer. For a rise in the oil of 35°C.

(63°F.), it is usual to allow from 4 to 8 sq. in. of tank surface per watt loss. Transformers which are cooled by water, or air, radiate heat from the tank walls in addition to transferring heat to the cooling medium. This radiation is usually small compared with the total and may be neglected in most cases.

Since the heat generated in a transformer comes from the core and windings, it is evident that there must be some difference in temperature between these parts and the oil. The only part in which the temperature is important is the winding. The difference in temperature between the oil and the windings will depend on the insulation on the coils. Bare coils, as sometimes used for low voltages, may be not more than 2°C. above the oil temperature. The usual type of insulated windings which have been carefully vacuum-treated and impregnated should not rise more than 5°C. above the hottest oil. Particular cases may be found where there is a difference in temperature rise between the oil and windings of as much as 10°C. This is due to a thicker insulation on the windings than is usual.

Terminals.—One very important feature of every high-voltage transformer is the terminals. It is through the terminals that the connections are made to the windings inside the case. The connections may be made either with a solid copper rod which forms the center of the terminal, or a lead may be passed through a hollow tube upon which the terminal is built. For voltages above 6600 volts, all terminals are in the top of the tank, extending through the cover. Below this voltage they may be put in pockets designed in the tank itself or in pockets, projecting downward at an angle with the vertical, which are formed in the rim casting, above the tank walls. Such construction is used for installation in manholes or out of doors where the cover is subjected to extreme dampness or precipitation and where there is not enough head room to permit terminals in the cover.

Up to about 6600 volts, a simple porcelain bushing is the only insulation that is required around the lead. For voltages up to 11,000 volts, the wire passing through the porcelain bushing should be well insulated. In some instances, an inside porcelain tube is used instead of insulation on the lead. In such a case the inside tube should be long enough to prevent creepage or flashover. Above 11,000 volts, a built-up terminal

is generally used. The lead is thoroughly insulated by suc cessive layers of fibrous material, the thickness of insulatio depending on the service voltage. This lead is cemented into porcelain bushing in the tank cover.

Where the voltage is of the order of 50,000 volts or abov some special type of terminal is necessary. The electrostati stresses induced by the high voltages will unduly strain th inside layers of a built-up insulator. The stress on the outsid layers will be very much less than on the first layers, and thi will become of extreme importance as soon as the insulatio thickness becomes heavy enough for 50,000-volt service. Ther are two general classes of high-voltage terminals now used the condenser type, and the porcelain shell filled with liquid o solid insulating material.

The condenser-type terminal is built up of alternate layers of insulation and thin metal until the proper number of layers has been applied. The metal layers form equipotential surfaces which will distribute the potential between the terminal and the cover (ground) in direct proportion to the insulation strength of the material used, provided the thickness of the layers of insulation and the lengths of each layer are correctly proportioned. Each layer of insulation with its metal layers on either side acts as a condenser, the completed terminal consisting of a number of condensers in series, distributing the potential between themselves in proportion to their relative capacities. The design must be such that the potential between any two successive layers is in proportion to the insulation strength between them. This may be accomplished either by applying layers of a thickness varying logarithmically, the lengths of each layer varying in an arithmetical proportion, or else the thicknesses of all layers may be the same, with the lengths of successive layers varying logarithmically. In some cases, the finished terminal built in this manner is all that is required. In other cases, when it is desirable to make the terminal shorter than would be required by the above method, a piece of thin sheet metal, in the form of a flattened surface of revolution, like the upper bell of an insulator, is placed on top of the terminal, the conductor passing through its center. This bell adds to the dielectric strength of the terminal by allowing a more uniform distribution of the electrostatic field. With the conducting bell, the field intensity at the end of each layer is very much reduced. This results in a more uniform dielectric stress on the insulating

materials. In addition to the conducting bell, there is sometimes added a shell of insulating material of uniform diameter. The space between the condenser and the outer shell is filled with insulating compound which is hard at normal temperatures. This compound has a high dielectric strength and increases the flashover voltage and resistance to creepage between successive layers of conducting material of the condenser at the ends of the layers. For outdoor service, the condenser is supported by, and carried in, a porcelain shell made up of a number of petticoat insulators cemented together and made waterproof. These insulators have holes pierced through their centers through which the terminals pass. They are assembled one above the other, to make a long, petticoated tube. This group takes the place of the tube in the case of the indoor type and increases the creepage distance from terminal to ground. The increased creepage distance is necessary during rainstorms when the insulator is wet. The space between the condenser and the porcelain is filled with a solid insulating compound in the same way as for the indoor type. Condenser-type terminals should be installed so that all of the metallic layers dip into the oil inside the tank. This allows the designer to shorten the terminal on the lower end. For a given service voltage, the dimensions of a condenser-type terminal are subject to wide variations. They may be made high and of small diameter, in which case, the conducting bell at the top may be left off. The other extreme is the short terminal of large diameter with a large conducting bell at the top. The choice between these two extremes, aside from cost, is a question of available space. With plenty of head room, the first extreme is perhaps the simplest. With limited head room, the shorter terminal must be resorted to. Since the terminals must be spaced far enough apart to prevent flashover between them, a large conducting bell will necessitate a large tank cover in order to allow sufficient clearance between terminals.

The second type of terminal for high voltage is made of a central hollow tube or conductor around which is placed a series of porcelain petticoats in much the same way as for the outdoor type of condenser terminal. The difference between the two is the difference in relative proportions of the series of petticoats. The condenser type usually has all of the petticoats of the same diameter, while the insulation-filled type has the petticoats of

gradually increasing diameter as they proceed downward from the terminal to the case. All joints between petticoats and between petticoats and the central conductor, are made oil tight. The terminal is filled with oil or solid insulating compound. In this country, the oil-filled terminal seems to be preferred. Abroad, the compound-filled terminal is largely used. There may be two or three metallic surfaces built in with the porcelain insulators. They serve the same purpose as the metallic layers of the condenser terminal. The oil-filled terminal has the advantage of instant repair of a breakdown through the terminal, and cooler operation due to the circulation of the oil. All terminals for high-voltage transformers will heat slightly, owing to dielectric hysteresis loss. The chief disadvantage of the oil-filled terminal is the necessity of frequent inspection to see that it is properly filled with oil. At the top of each terminal is placed a small glass section in which the oil level may be observed. Any leak in the terminal will cause breakdown as soon as the oil drains out. The condenser terminal, or the terminal with solid insulation, places all weak points in series, as the equipotential surfaces pass entirely around the terminal.

Extreme care must be used in manufacture of any high-voltage apparatus in order to insure good workmanship and the use of none but the best materials. All contracts for high-voltage terminals should contain clauses regarding testing. The large manufacturers now have standard tests which include the measurement of flashover voltage and the maximum voltage without the appearance of corona, on a few of a lot, and certain routine tests on partially completed units. For outdoor service the tests are made under rain conditions as well as dry. One manufacturer uses the following test for condenser terminals. The completed condenser is tested for 48 hr. at 115 per cent. of normal voltage between the central conductor and a band corresponding to the tank cover. It is then subjected to 275 per cent. normal voltage for 1 min. before assembly. The completed terminal is tested under the conditions agreed upon between the manufacturer and the purchaser. These should include a test at double normal voltage for 1 min. without signs of distress or corona.[1]

[1] See "The Condenser-type Outlet Terminal," by FORTESCUE and MATEER, *Electrical Journal*, August, 1913.

"High-voltage Transformer Leads," by EBY, *General Electric Review*, June 1913.

Single-phase vs. Three-phase Transformers.—*Either* three-phase or single-phase transformers may be used for a three-phase transmission system. For a given kilovolt-ampere capacity the three-phase transformer is cheaper than three single-phase transformers. As in the case of generators, spare units must be provided, and, for an installation of single-phase units, one extra transformer is all that is usually required. The investment in spares is thus less with the single-phase units. It is not usually desirable to build three-phase units for high voltages, as it is necessary to increase the size of the transformer in order to properly insulate it. It is easier to handle the smaller single-phase unit in case repairs are necessary. A further advantage of single-phase units is that two single-phase transformers may be used for three-phase transformation should one unit of a bank of three break down. The faulty unit is disconnected and removed and the other two will carry 58 per cent. of the load (not 67 per cent.) with the same heating as before the breakdown. Such a bank will not parallel successfully with a three-unit bank, because the regulation is worse, and the voltage drop on one of the phases is slightly greater than on the other two. However, such an arrangement is very desirable where each transformer bank supplies a single feeder and where continuity of service is important. This combination is possible with only one system of connections, namely, delta connection of both primary and secondary circuits of the transformers, and technically termed delta—delta. Very nearly half of the large, high-voltage systems use this connection.

Installation Out of Doors.—Transformers may be installed outdoors by a slight change in the terminals, as before noted under the subject of terminals. The outdoor installation is cheaper since there is no building required to house the apparatus. Water-cooled apparatus should not be installed out-doors, unless special precautions are taken to prevent freezing of the water in winter while idle. A water-cooled transformer would soon overheat and burn out if the water supply were shut off. There is also the danger of the water freezing in the cooling coils and bursting the pipe. The losses in a transformer are sufficient to keep it from freezing, even when carrying no load.

Tests.—The guarantees which are given for transformers usually include the following: efficiency, regulation at 100 per cent. and 80 per cent. power factors, and temperature rise at

full load and overloads. In addition to these, statements are usually included in regard to insulation strength, as follows: insulation between turns will be sufficient to withstand double normal potential, and the insulation to ground and between high- and low-tension windings will be sufficient to withstand voltages as prescribed by the standardization rules of the A. I. E. E. The A. I. E. E. rule is: "The standard test for all classes of apparatus, except as otherwise specified, shall be twice the normal voltage of the circuit to which the apparatus is connected, plus 1000 volts." Thus, a transformer with primary voltage of 2200 volts and secondary voltage of 66,000 volts would be tested at 5400 volts between low-tension winding and core and at 133,000 volts between high-tension winding and core and low-tension winding, the low-tension winding being connected to the core. In the case of star-connected transformers, the test is based on the line voltage of the circuit on which the transformer is to operate. The tests are best conducted at the place of manufacture since the manufacturer has the facilities for testing. Some of the tests may be made after the apparatus is installed. If requested at the time when the order is placed, manufacturers will make a certified report of the tests, or perform them in the presence of the purchaser, for a small additional charge. The tests are made as follows.

Efficiency is measured from the losses. The A. I. E. E. rules include the no-load losses; copper, or I^2R losses, and stray load losses. The no-load losses are measured with open secondary circuit at the rated frequency, and with an applied primary voltage giving the rated secondary voltage plus the IR drop which occurs in the secondary under rated load conditions. It is assumed that the voltage wave is approximately sinusoidal, since the wave shape will effect the no-load losses. In practice, the secondary IR drop is small and is usually neglected. The copper, or I^2R, loss is calculated from the measured resistances of the windings at a specified temperature and the current which each winding is to carry.

The stray load losses are measured by applying a primary voltage sufficient to produce rated-load current in the primary and the secondary windings, the latter being short-circuited. The stray load losses will then be equal to the input required to produce these full load currents, minus the measured I^2R losses in both windings, as computed from the resistance measurement

at actual temperature, and the rated current. It is, ordinarily, immaterial whether the high-voltage or low-voltage winding is used as the primary winding in this test. In many instances the stray load losses are neglected, and the basis of efficiency determinations is stated when giving figures for efficiency. Knowing the losses, the efficiency may be computed as the ratio of the rated output to the sum of the rated output plus the losses.

Regulation is defined as being the change in the secondary terminal voltage with change from full rated load to no load at the specified power factor (the primary impressed terminal voltage being held constant), and expressed as a percentage of the full-load secondary voltage. It is not usually possible to load a large transformer and measure directly the change in secondary voltage. Moreover, the change in voltage is so small that it is difficult to measure accurately. The value may best be calculated from the test for stray losses, as described below (which is frequently called the *impedance test*).

Let W = watts input at rated primary current.

E_z = applied voltage required to circulate this current.

$\cos\phi$ = the assumed load power factor, ϕ being the angle by which the current lags behind the voltage for the given load conditions.

$$E_r = IR = W/I \qquad (1)$$

where I is the rated primary current and E_r = voltage drop due to resistance of windings.

$$E_x = \sqrt{E_z^2 - E_r^2} \qquad (2)$$

E_x = voltage drop due to inductance of the windings.

If E is the rated primary voltage, then the percentage regulation is expressed by the formula

$$\frac{\text{Per cent. } R}{100} = (E_r/E)\cos\phi + (E_x/E)\sin\phi + \frac{\{(E_x/E)\cos\phi - (E_r/E)\sin\phi\}^2}{2} \qquad (3)$$

It is usual to neglect the last term since it is a small part of the total.

A numerical example will illustrate the use of the above formula.

A transformer of 500 kv.a. capacity, 66,000 to 2200 volts gave the following results on impedance test.

At rated current of 7.57 amp. in the high tension winding and with the low-tension winding short-circuited, voltage applied to the high-tension winding was 2300 volts, and the energy input, 7220 watts. Then,

$E_r = 7220/7.57 = 954$ volts and from the test readings
$E_z = 2300$ volts. Therefore,
$E_x = \sqrt{2300^2 - 954^2} = 2093$ volts. Then

$$\frac{E_r}{E} = \frac{954}{66{,}000} = 0.0145, \text{and}$$

$$\frac{E_x}{E} = \frac{2093}{66{,}000} = 0.0317$$

The regulation at 100 per cent. power factor, or for $\cos \phi = 1$, is then

$$\frac{\text{Per cent. } R}{100} = 0.0145 \times 1.0 + 0.0317 \times 0.0 + \frac{\{0.0317 \times 1.0 - 0.0145 \times 0.0\}^2}{2}$$

$$= 0.0145 + 0.0005 = 0.015, \text{ or } 1.5 \text{ per cent.}$$

At 80 per cent. power factor this becomes

$$\frac{\text{Per cent. } R}{100} = 0.0145 \times 0.8 + 0.0317 \times 0.6 + \frac{\{0.0317 \times 0.8 - 0.0145 \times 0.6\}^2}{2}$$

$$= 0.0116 + 0.0190 + 0.0003 = 0.0306, \text{ or } 3.06 \text{ per cent.}$$

It is seen that in the calculations the last term is negligible. The derivation of this formula is long and complex, and is not attempted here. It is the formula given by the A. I. E.. E. standardization rules.

The temperature rise guarantees usually given for transformers are the same as for generators; 40°C. rise on continuous full load and 55°C. rise on 25 per cent. overload for 2 hr. immediately following full-load operation. The "maximum rating" is more frequently applied to transformers than to generators. The heating tests should be made under, approximately, full-load conditions. In order to do this with single-phase transformers, two or three units must be used. For two units, the

connections are as shown in Fig. 16. For three units, the connections are shown in Fig. 17. In these figures, E_M denotes a source of power from which the magnetizing current is obtained at full rated voltage of the winding to which it is applied; in the one case, a single-phase voltage, in the other, a three-phase voltage. E_Z indicates the source of power from which the impedance loss is supplied, the voltage of which is just sufficient to circulate full-load current in the winding to which it is applied. E_Z, is, in all cases, a single-phase voltage. It is to be noted that in the case of two units the primary windings are connected in parallel. In the case of three units they are connected in delta. This latter method is also applicable to three-phase units. The secondaries are always in series. Current is supplied to the transformers and kept flowing until they have attained a constant temperature. This point may be approximated very closely by

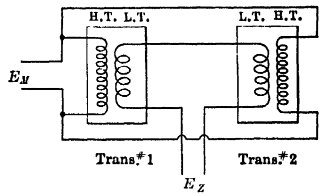

FIG. 16.—Connections for heat test. (Two units.)

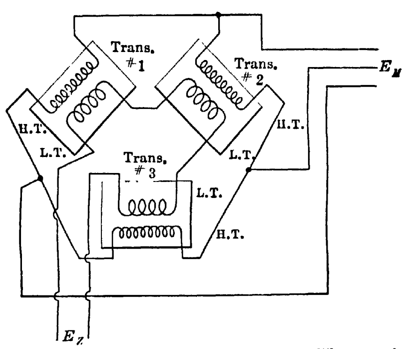

FIG. 17.—Connections for heat test. (Three units.)

noting the temperature of the oil in the top of the transformer tank. When these temperatures have been constant for at least 2 hr., it may be assumed that the transformer has attained maximum temperature. The temperature rise of the windings is measured by the increase in their resistances. The resistances of both the low- and high-tension windings are taken before begin-

ning the test at some known temperature, t, when the windings and the surrounding air are at the same temperature. At the close of the heating test the transformer is disconnected and the resistances are quickly taken. The temperature rise, above the temperature at which the initial resistance was taken, is given by the formula

$$t_i = \left(\frac{r_2 - r_1}{r_1}\right)(234.5 + t) \tag{4}$$

t_i = temperature rise in deg. C.
r_1 = resistance of windings at initial temperature.
r_2 = resistance at increased temperature.
$234.5 + t$ = absolute temperature C.

The temperature rise must be corrected for the change in temperature of the cooling medium between the time when the initial resistance was taken, and when the heat run ends. It is to be noted that the temperature rise is measured above the temperature of the incoming cooling medium. In self-cooled apparatus this is the surrounding air, in water-cooled apparatus it is the incoming water, and in air-blast apparatus it is the incoming air. A numerical example will illustrate the use of this formula.

Resistance of high-tension winding at 20°C. = 1.2 ohms. At the end of the heat run the high-tension resistance was 1.4 ohms and the cooling medium was 25°C. Then

$$\text{temperature rise, or } t_i, = (234.5 + 20)\frac{1.4 - 1.2}{1.2} = 42.4°\text{C.}$$

The cooling medium has risen 5°C., so that the temperature rise of the winding above the cooling medium is 42.4 − 5 = 37.4°C. The temperature of the cooling medium should not vary more than 5°C., or at most, 10°C. during the run. The temperature of the cooling fluid is to be taken as the mean of readings observed at equal intervals of time during the last quarter of the duration of the test. It has been found by tests that the temperature of the cooling medium, within the limits to be found in usual practice, has little or no effect on the temperature rise of electrical machinery.

The tests for insulation strength should be carefully made. It is customary to *gradually* raise the voltage to the required value, hold it there for the required length of time, and then remove it by lowering the voltage.

The author has always required that in every case, the test voltage should be begun at the normal working voltage, then the higher test voltage *switched directly* on to the apparatus. Tests which are made by starting with normal voltage and gradually raising to the test voltage have no practical value, although this is the practice of most of the companies manufacturing electrical apparatus. In service, any excessive voltage is sure to be suddenly applied, and the test voltage should be applied in the same manner.

It has been recommended that materials which are present in the usual transformer should not be subjected to temperatures higher than 105°C. It is assumed that the hottest part of the windings is 10°C. above the mean temperature as found by the resistance method. This permits of a maximum observable temperature of 95°C. or a temperature rise of 55°C. above a cooling medium temperature of 40°C. When measurements are made by thermometers, this difference is taken at 15°C., and the maximum observable temperature should not be over 90°C.

Oil.—The oil in which oil-insulated transformers are immersed should be a good grade of mineral oil free from sulphur or moisture, with as low a viscosity as consistent with high flash point and high burning point. In addition to these qualities, it must have a high dielectric strength. Before testing the oil it should be thoroughly dried and filtered. There are machines on the market for this purpose. The oil is pumped through a series of layers of a blotting paper which removes impurities and most of the water or moisture. It is impossible to remove all of the water, except by special apparatus. After transformers have stood for a time it is possible to draw oil off from the bottom of the tank which has a large percentage of moisture in it. The water, being heavier than the oil, settles to the bottom. Oil should be tested periodically, the sample being taken from the top of the tank. At least once a year the oil should be removed entirely and refiltered. The oil should be removed from the bottom of the tank, the first portion, which is high in moisture, being discarded. After a small amount has been withdrawn, a sample should be taken and tested. Unless the tests show the oil to have standard dielectric strength, it should be discarded, or else specially treated to remove the excess moisture. The presence of moisture in oil greatly reduces its dielectric strength.

Average oil should show a dielectric strength of at least 30,000 volts when tested between spheres ½ in. in diameter and separated by 0.15 in. For very high-voltage transformers this value should be increased to 40,000 volts. In order that the oil will circulate freely it should have a low viscosity. In addition, since it is the means of removing heat from the transformer, it should have a high flash point. Viscosity and flash point will usually vary together, an oil of low viscosity having a low flash point. The flash point of an oil for self-cooled transformers should not be below 175°C. and for water-cooled apparatus it should not be below 125°C. The distinction is made here because the operating temperature of the oil in a water-cooled transformer is lower than in the self-cooled type. The flash point of oil is the lowest temperature at which the vapors given off from the surface will ignite in flashes without combustion. When combustion takes place, the temperature of the oil has reached its burning point. The burning point of the oil should not be lower than 200°C. and 150°C., respectively, for self-cooling and water-cooled transformers. All of the tests made on oils depend on conditions of test. The exact procedure to be followed in each case should be specified. The dielectric strength will depend upon the frequency and the wave shape. A 60-cycle sine wave is recommended.

Oil may be shipped in the transformer when special precautions are taken to prevent the motion of the oil. The tank should be completely filled, due allowance being made for change in volume with temperature, and the cover should be air-tight to keep out moisture. It is usually better to ship the oil separately in steel drums. Oil should never be shipped in wooden barrels since they are not moisture proof. The drums should be clean and used for transformer oil only. Manufacturers keep in stock various sizes of steel drums for this purpose which are loaned to the purchaser.

Installation Indoors.—The best practice is to use a separate fireproof compartment for each transformer when they are installed indoors. The front of the compartment may be closed with an iron door which is either hinged or sliding. The compartments should be large enough to permit access to inspect the tank from all sides. When transformers are not installed in compartments, but are placed in a separate room, they should be put far enough apart to allow a man to easily pass between them.

The tanks, or cases, of all transformers should be thoroughly grounded to prevent the formation of static charges dangerous to the attendant. All transformer rooms should be well ventilated to allow the escape of hot air and the inflow of cool air.

Water-cooled transformers may be run on overloads greater than 25 per cent. for a short period of time by increasing the water rate. They are regularly provided with a thermometer which is attached to a pipe plug in the tank at a height just below the oil level. If the attendant is required to watch these thermometers carefully, it may be found possible to carry the load on a smaller number of units than would be necessary if there were no supervision. Should the temperature become too high, another bank may be put into operation. A thermometer should always be required in all transformer specifications. Air-cooled apparatus may have a thermometer in the air outlet or may have some form of resistance thermometer or thermocouple. With electrical thermometers one instrument on the switchboard may be used with any number of transformers. Each resistance or thermocouple is connected to the switchboard in such a way that any one may be connected to the instrument by the insertion of a voltmeter plug in the proper receptacle.

Efficiencies.—Transformers have high efficiencies. The following table shows efficiencies for transformers of, approximately, 14,000 volts maximum, for 60-cycle service.

TABLE 1.—TRANSFORMER EFFICIENCIES

Kv.a.	Efficiency at full load	Cooling
100	97.2	Self
200	97.8	Self
300	98.0	Self
500	98.2	Self
500	98.0	Water
1000	98.4	Water
2500	98.8	Water

For 25-cycle service, the corresponding efficiencies will be about ½ per cent. lower. It is usual to so proportion the losses that the maximum efficiency shall occur at, or near, full load. The efficiency is maximum when the core loss and the copper loss are equal. It is thus usual to find that the full-load loss is made up

equally of core and copper losses. Certain design features may make it advisable to change this proportion of losses, or else it may be that the service is such that the load on the transformers may be other than rated load the greater part of the time. It would then be advisable to change the proportion of losses so that the maximum efficiency shall occur at that load which will be carried the greater part of the time.

The regulation of transformers, as shown by formula (3) will vary with the power factor. The regulation of the transformers given in table 1 will vary, approximately, from 2 to 0.9 per cent. at 100 per cent. power factor, and at 80 per cent. power factor will vary from 7 to 3.5 per cent. In general, transformers for higher voltages will have lower efficiencies than those given and their regulation will be worse.

If transformers are to be purchased for operation in parallel with existing units, the manufacturer must know the impedance of the old units as well as the number of turns on each winding. The new units must have exactly the same ratio of transformation, that is, the same ratio of high- to low-tension turns, or else they will not divide the load properly and no amount of external apparatus, except boosting transformers, will correct this error. If the ratio is correct, transformers in parallel divide the load inversely as the impedances. Thus, two transformers of rating as 1:2 must have impedances in the ratio of 2:1 in order to divide the load in proportion to their respective ratings. The impedance is the value, measured in the "impedance test," of the voltage necessary to circulate full-load current in the short-circuited secondary, voltage being applied to the primary.

Connections.—The primaries and secondaries of a three-phase transformer, or three single-phase units for three-phase transformation, may be connected in either one of two ways; star (Y), or delta (Δ). The delta connection is sometimes called "mesh" connection. These are shown in Fig. 18. The primaries and secondaries need not be connected the same way. For example, the low-tension side may be delta-connected while the high-tension side may be star-connected. When transformers are to be operated in parallel, the system of connections of each bank must be of such a nature that parallel operation is possible. The following table shows at a glance the various possibilities. Those combinations marked "NO" are impossible because of

the fact that, while the primary voltages are in phase, the secondaries cannot be placed in phase.

TABLE 2.—TRANSFORMER CONNECTIONS

	YY	YΔ	ΔΔ	ΔY
YY	YES			
YΔ	NO	YES		
ΔΔ	YES	NO	YES	
ΔY	NO	YES	NO	YES

Of the four possible systems of connections, but three are used extensively. The star-star connection has inherent disadvantages due to distortions in voltage among the phases. The neutral point, where the three phases are connected together, is not electrically fixed. With unbalanced load, or unsymmetrical transmission, the voltages of each phase to neutral are unequal. This produces what is termed a "floating neutral" and causes further unbalancing which is emphasized when supplying a long transmission line. The regulation of such a combination is bad, and the transformer with the highest voltage is working under abnormal conditions which may cause serious overheating due to high core loss with increased voltage and flux. If the neutral of the high tension windings is grounded, there will be a third harmonic charging current from the line to the neutral, which may seriously effect neighboring telephone circuits. The third harmonic is caused by the presence of iron in the core of the transformer. The exciting current of a single-phase transformer contains a prominent third harmonic due to the varying permeability of the core at different values of density. The permeability varies through a single cycle due to the variation in flux density in the core. There is no path for a third harmonic of current to flow in star-connected transformers (since a sine wave of impressed voltage on a three-phase system necessitates a sine wave current), hence, the voltage to neutral must contain

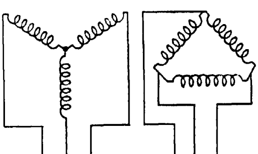

FIG. 18.—Transformer connections.

a third harmonic. This third harmonic of voltage is the cause of the third-harmonic charging current flowing from the transmission line to the grounded neutral. It is generally conceded that the star-star connection is not desirable, with the neutral either grounded or insulated. With the delta connection, in either the high- or low-tension winding, the third-harmonic current is induced in the windings and flows around through the windings.

The delta-star connection is widely used for raising the generator voltage to the line voltage. The usual practice is to ground the neutral on the high-tension side, directly, or through resistance. Inasmuch as the third-harmonic exciting current is supplied in the low-tension delta winding, there will be no third-harmonic voltage on the high-tension side, thus eliminating the third-harmonic charging current. By the use of protective relays in the neutral and in each line, circuit-breakers may be automatically opened when a ground occurs on the line before a short-circuit can be established between phases. This is also of importance with the star connection, because if one transformer should become short-circuited, the full line voltage is impressed across the terminals of the other two, causing a rise of potential in them which is 173 per cent. of the normal voltage. The voltage from any one line to neutral is 1/1.73 or 57.7 per cent. of the line voltage. Hence, for a given line voltage, the voltage of any one of these star-connected transformers needs to be only 58 per cent. of the line voltage. Mesh-connected transformers, however, must produce the full line voltage in their windings. If a resistance is connected between the neutral point of a star-connected system and the ground, it is usually made large enough to limit the current to a value which will just operate the protective relay, or to a value not to exceed full-load current.

The star-delta connection is generally adopted for stepping down the line voltage when the reverse connection is used for stepping up. It is usual to insulate the neutral of the step-down transformers.

The delta-delta connection is the most widely used at the present time, though the tendency now is to use the delta-star in its place for raising the voltage. The operating advantage of the delta-delta connection has been already spoken of.

The current and voltage relations in star and delta three-phase transformation are as follows. The star connection winding

carries the full line current, and the voltage across one phase is 57.7 per cent. of the line voltage. Hence, the cross-section of the copper is larger than for the delta connection, and the number of turns required is smaller in proportion to the line voltage. This makes a stiffer coil which is better able to withstand the

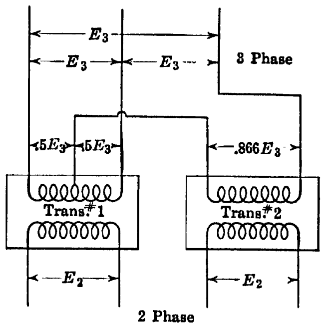

FIG. 19.—Transformer connections; two-phase to three-phase.

mechanical stresses which exist between conductors carrying current. This is of particular importance under short-circuit conditions where the stresses may reach values large enough to distort the coils unless precautions are taken to securely brace

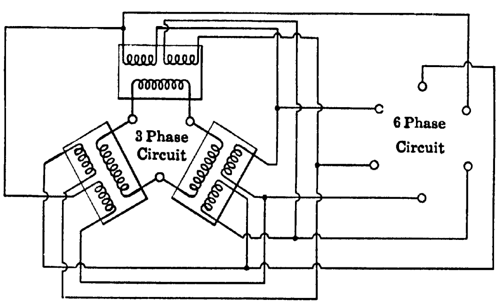

FIG. 20.—Transformer connections; three-phase to six-phase; double-delta.

them. All transformers are carefully built to insure rigidity of the windings under large forces.

It sometimes becomes necessary to change from three-phase to two-phase, or *vice versa*. This may be accomplished by using two transformers, connected as shown in Fig. 19. This connection is called the "Scott connection."

Rotary converters are largely used for changing from alternating current to direct current. The larger the number of phases on the alternating-current side, the smaller does the converter become for a given output. It is, therefore, desirable to change from three-phase to six-phase for use with rotary converters. This may be accomplished in two ways, the double delta, or double star (sometimes called diametrical star). In either case three transformers are required. The connections are as shown in Figs. 20 and 21. With the double-delta connection, it is seen that the secondary is made of two windings on each phase of the three-phase bank.

There are other methods of obtaining phase transformation, from three-phase to either two- or six-phase. These are made of

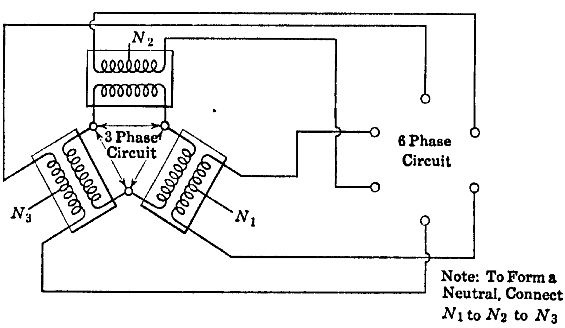

FIG. 21.—Transformer connections; three-phase delta to six-phase diametrical star.

two units but they are all unbalanced in voltage and are seldom used.

In order to connect transformers in parallel, the polarity must be determined. The polarity of single-phase units is very simply checked by connecting together one high-tension lead and one low-tension lead, applying voltage to either the high- or low-tension winding, and measuring the three possible voltages. The voltage between the two leads not connected together may be either greater, or less, than the high-tension winding voltage. Two units to be connected in parallel, should be checked in this manner, and the leads connected together in the test, should be so arranged that all of the voltages are of the same value in the two transformers. The transformers may then be paralleled

by connecting the high-tension lead, which was connected to the low-tension lead on test, to the same high-tension terminal in both cases, the low-tension being connected in a similar manner. Three-phase units may be checked in a similar manner, but the method is long and complicated because of the numerous possible combinations. It is usually simpler to compare two transformers which are to be paralleled. To do this it is necessary to connect either the high- or low-tension windings of both transformers to some source of voltage, then connect any one lead of the other winding of one transformer to any lead of the corresponding winding of the other transformer and read the voltages between any pair of leads from one transformer to the other. The leads on the unconnected windings may be shifted until all voltages become zero. The leads then connected are the proper leads to connect together for parallel operation. Tbe meter used for measuring the voltage should have a range double that of the voltage between two leads on one transformer. This method may be used for single-phase units and is to be preferred for installation purposes.

Insulation of End Turns.—All transformers on transmission lines should have extra insulation on the windings nearest the line, that is, on the end turns. Any surges which may come in from the line are particularly dangerous in this portion of the winding and the voltage per turn may be many times greater than the normal. The reason for this is at once apparent when it is considered that most of these surges are high-frequency impulses. The reactance of the transformer winding is proportional to the frequency, so that the voltage drop, at high frequency, is very large for even a moderate current, due to the high reactance. The usual practice is to place some extra insulation between each turn in the end coils, and extra insulation between layers. It is not possible to give any definite rule as to the number of turns to be considered "end turns" and to be given extra insulation. This is largely a question of judgment on the part of the designer. His decision is based upon the voltage of the system, the system of connections, and the nature of the territory served by the system. It is not usual to give any particular test to the end turns, in addition to the regular tests. If desired, arrangements may be made for so doing, at an additional expense. The end coils are then tested alone, before assembly, in a manner to be agreed upon.

The voltage per turn may be anywhere from three to five, or more, times the normal voltage per turn.

Methods of Switching.—The question of the proper method of switching transformers on and off the line is interconnected with the line design and is treated in the chapter on "Switchboards." Practically all surges originate in the line rather than in the transformer. Low-tension switching is to be preferred in switching on a line, because the inductance of the transformer will damp out the surge on the line to some extent. For such a procedure the high-tension switches are first closed, connecting the transformers to the line. The connections are then made from the generators to the transformers. Where low-tension switching is not possible, it has sometimes been considered advisable to insert inductance in the switching operation, the inductance being short-circuited when the high-tension switches are finally closed. Rather than to provide facilities to prevent surges, it is usually found that the installation of safety appliances, such as horn gaps or lightning arresters, is preferable.

When laying out a system it is the best plan to investigate other systems, comparing the conditions existing there with those to be expected in the new system and profiting by the experience there gained. The art has not yet advanced far enough so that it is possible to lay out definite rules for the selection of any part of the apparatus. The engineer must use his own judgment in connection with the experience of others.

Theory.—The theory of the operation of the transformer is very simple. As described in the first part of this chapter, the transformer consists of one or more electric circuits interlinking one or more magnetic circuits. A voltage is applied to the primary winding, the voltage varying with time, according to a sine law. A flux is induced in the magnetic circuit, of such a value that it will induce in the primary winding an e.m.f. equal and opposite to the applied voltage. This is not exactly true, because of the resistance and reactance of the primary winding. For the purposes of calculating the magnetic circuit, the impedance drop in the primary winding is negligible. From the fundamental equation of the induced voltage

$$e = -\frac{d\phi}{dt} \tag{5}$$

e, ϕ and t being respectively the voltage, magnetic flux and time all in fundamental, or *C. G. S.*, units. The equation shows

that the voltage is proportional to the rate of change of flux and is opposed to it. In order to induce a voltage wave of sine shape, the flux wave must be of sine shape. Assuming, then, the flux to vary according to the sine law, it is apparent that the flux and voltage are in quadrature, that is, the voltage leads the flux by 90 electrical degrees (see explanation in chapter on "Electric Circuits"). At any instant the flux may be found by the equation

$$\phi = \phi_m \cos 2\pi ft \tag{6}$$

in which ϕ_m is the maximum value of the flux at any instant, f is the frequency of the pulsation in complete cycles per second, and the flux has a value ϕ at any time t, the time of starting ($t = o$) being arbitrarily assumed. Substituting the value of ϕ in the fundamental equation,

$$e = -\frac{d\phi}{dt} = -\frac{d\,(\phi_m \cos 2\pi)ft}{dt} = 2\pi f\phi_m \sin 2\pi tf \tag{7}$$

Thus the maximum value of the induced voltage *per turn*, is

$$E_m = 2\pi f\phi_m \tag{8}$$

and the effective, or $\sqrt{\text{mean square}}$, value of the induced voltage is, therefore,

$$E = \frac{2\pi f\phi_m}{\sqrt{2}} = 4.44 f\phi_m \tag{9}$$

This equation is expressed in C.G.S. units. The practical unit, or volt, is 10^8C.G.S. units. Hence, to reduce to practical units with the flux in *lines*, and with N_1 primary turns in series, the formula by which the flux is computed from the induced voltage, or *vice versa*, is

$$E_1 = 4.44\, fN_1\phi_m\, 10^{-8} \tag{10}$$

The voltage induced in the secondary winding, *per turn*, must be the same as for the primary, since the same flux interlinks both windings. The secondary voltage is, therefore, found from the above equation by the substitution of the number of turns in the secondary winding. The ratio of transformation is, therefore, the same as the ratio of turns connected in series.

In order to produce a flux through, and overcoming the reluctance of the steel, (the reluctance is analogous to resistance of the electric circuit) it is necessary to have a magnetizing

force. This magnetizing force is expressed in ampere-turns and is the product of the current flowing and the number of turns interlinking the magnetic circuit. The current which excites the transformer is called the magnetizing or exciting current. Neglecting core loss, which consumes power and draws a current in phase with the impressed voltage, this exciting current is in phase with the flux, and hence lags 90° behind the impressed voltage.

The equivalent resistance (or reactance) of a transformer is such a resistance (or reactance) which, if placed in the primary circuit, will produce the same voltage drop as in the actual transformer. Denoting by T the ratio of transformation,

$$T = N_1/N_2 \tag{331}$$

N_1 and N_2 being the number of turns in the primary and secondary windings, respectively. Then the resistance of the secondary winding expressed in terms of the primary is R_2T^2, and the total equivalent transformer resistance is $R_1 + R_2T^2$. R_1 and R_2 being the resistances of the primary and secondary windings, respectively. This may be shown to be true as follows: Consider a transformer of voltage ratio 1000 to 100, or T, the ratio of transformation = 10. Suppose a current of 1 amp. to flow in the primary. The current in the secondary, in order that the input may equal the output (neglecting losses), must be 10 amp. A resistance of 10 ohms in the primary circuit, will cause a drop of 10 volts, or 1 per cent. of the primary voltage. In order to produce a drop of 1 per cent. in the secondary winding the voltage drop must be 1 volt. With a current of 10 amp. the resistance must be 0.1 ohm. It is thus seen that a primary resistance of 10 ohms has the same effect as a secondary resistance of 0.1 ohm. As stated the equivalent primary resistance is found to be $R_2T^2 = 0.1 \times 10^2 = 10$ ohms which is the value assumed for the primary resistance. It may be similarly shown that the reactances have the same relation, or,

$$\text{total reactance} = X_1 + X_2T^2.$$

X_1 and X_2 being the reactances of the primary and secondary windings, respectively.

All of the foregoing factors may be grouped together to show the action of the transformer. The performance is best shown by a vector diagram as in Fig. 22. The vector of induced

voltage, E'_1, is taken as the vector of reference, and drawn vertically upward. The impressed voltage is found from this by adding the resistance and reactance drops in the primary winding. The resistance drop is in phase with the primary current, I_1, and the reactance drop in leading quadrature to it. The flux ϕ, is in lagging quadrature with the induced voltage, and the magnetizing current, I_M, is in phase with the flux. The no-load current necessary to supply the no-load losses, is shown in phase with the induced voltage, and is equal to I_c.

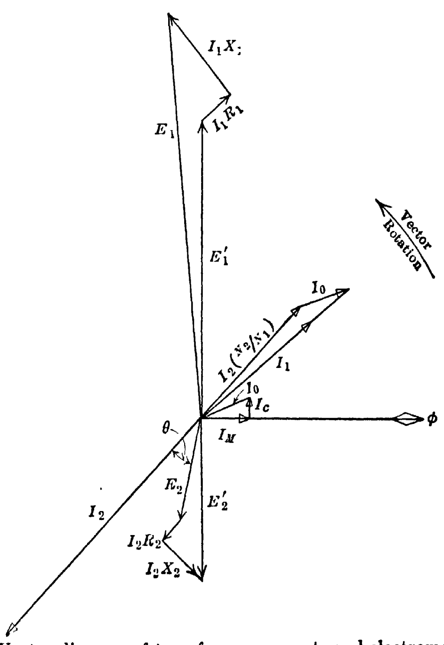

FIG. 22.—Vector diagram of transformer currents and electromotive forces.

The total no-load current is thus the vector sum of I_M and I_c and is equal to I_0. The secondary current is equal and opposite to the primary current minus the no-load current, and has a value determined by the ratio of transformation. I_2, is shown as the secondary current, and $\frac{I_2N_2}{N_1}$ is its equivalent primary value. The secondary terminal voltage, E_2, is the difference between the secondary induced voltage, E'_2, and the drop

in the secondary winding. The secondary resistance drop is in phase with the secondary current, and the reactance drop is in leading quadrature with it. This diagram is exaggerated for clearness. In the actual transformer, I_1 and I_2 are about equal and opposite (taking them in the terms of one winding) and the impressed and secondary voltages are likewise equal and opposite (considering voltage per turn). The no-load current is usually very small, not over 10 or, perhaps, 15 per cent. of the rated full-load current.

Auto-transformer.—Where it is not necessary to isolate the primary and secondary circuits, an auto-transformer may be used for changing the voltage of an alternating-current system with considerable saving in first cost. An auto-transformer is built in a similar manner to a transformer, except that there is but one winding. The proper voltage is obtained for the low-voltage circuit by tapping off at the proper number of turns. An auto-transformer winding is shown diagrammatically in Fig. 23. The arrows indicate the instantaneous directions of current flow.

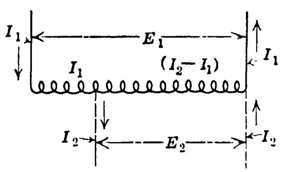

FIG. 23.—Connections of auto-transformer.

It is seen that a portion of the winding, $\frac{(E_1 - E_2)}{E_1}$, carries the current I_1, and a portion of the winding, E_2/E_1, carries the current $(I_2 - I_1)$. The necessary capacity of the first portion of the winding is $I_1(E_1 - E_2)$ watts, while that of the second portion is $E_2(I_2 - I_1)$ watts. The average rating of the two portions is thus,

$$W = \left\{\frac{I_1(E_1 - E_2) + E_2(I_2 - I_1)}{2}\right\} \text{watts} \qquad (13)$$

Since the input is equal to the output, $E_1I_1 = E_2I_2$ and the above equation reduces to $I_1(E_1 - E_2)$ as the rating of the auto-transformer. This factor is known as the "equivalent transformer rating" and determines the size of the auto-transformer. It is seen that the nearer do the primary and secondary voltage approach each other, the smaller does the auto-transformer become. The rating of a transformer to do the same work would be E_1I_1. Hence, the auto-transformer is smaller than the transformer in the ratio of $(E_1 - E_2)$ to E_1.

Auto-transformers are frequently used to tie together two transmission systems which operate at different voltages. In such a case it is not necessary to insulate one from the other. Where the object is to step up (or down) the voltage to (or from) the transmission line it is essential to insulate the primary winding from the secondary winding, and a transformer is here necessary. Auto-transformers are used for starting alternating-current motors by applying to the motor terminals reduced

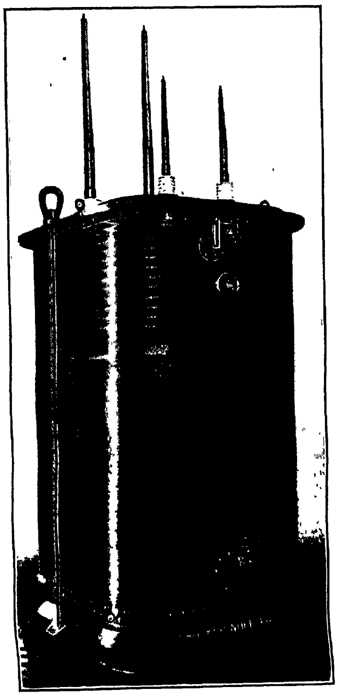

FIG. 24.—Transformer in case, complete. Showing porcelain tube terminals.

voltage. The purpose is to reduce the current drawn by the motor during starting. As soon as the motor has come up to speed, it is thrown directly on the line and the auto-transformer is disconnected.

Series Transformer.—A type of transformer which is different from the foregoing types, is used for measuring current flowing

in any line. This transformer is called a series transformer and is used for metering purposes, or for operating relays to open automatic switches in case of overload. Use is made of the principle that the ampere-turns of the primary winding must equal the ampere-turns of the secondary winding. The secondary winding is short-circuited through an ammeter, or relay coil, of low impedance. The transformer core is run at a very low flux density in order to reduce magnetizing voltage. As long as the secondary is short-circuited, the impedance of a

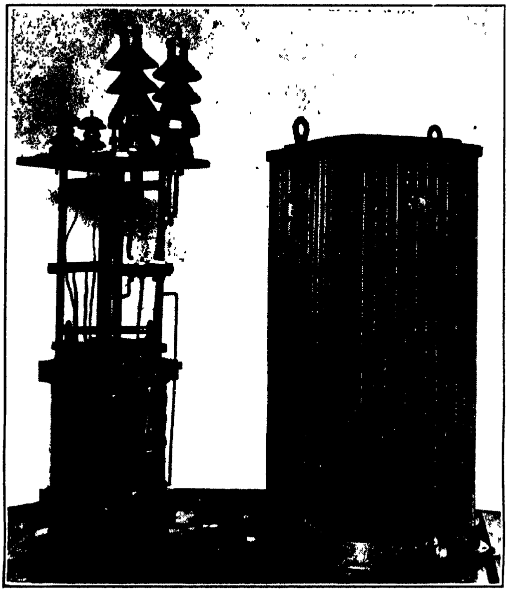

FIG. 25.—Transformer out of case. Showing porcelain petticoat terminals

series transformer is small, but on open circuit this impedance increases greatly. The number of turns on the secondary winding is large as compared with the primary (in order to reduce the current value in the secondary) and the voltage induced in an open-circuited secondary would be dangerously high. Whenever it becomes necessary to disconnect an ammeter or relay coil which is fed from a series transformer, *always* short-circuit the secondary winding directly through a low-resistance jumper *before* disconnecting the instrument or relay.

Figure 24 shows a phantom view of a complete water-cooled transformer in its case. The cooling coil and the electrical windings and terminals are all plainly visible.

Figure 25 is a transformer taken out of its case, the porcelain petticoat terminals being clearly shown.

CHAPTER III

SWITCHBOARDS

Switchboards for hydro-electric plants comprise both alternating- and direct-current sections. The direct-current system is supplied by the exciters, and the energy from these is distributed from the direct-current busbar to the fields of the main generators. The direct-current portion of the board is similar in every respect, to that of any other direct-current board except that instead of ordinary feeder switches, a special form of generator field switch is used, which is later described.

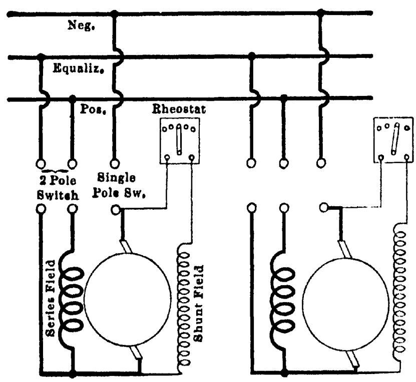

FIG. 26.—Connections for compound-wound, direct-current generators in parallel.

Where the exciters are compound-wound, it is necessary to provide an equalizer busbar, the connections for two or more exciting units being as shown in Fig. 26. It is better practice to use one double-pole and one single-pole switch instead of a triple-pole switch in the connection from generator to busbars.

Current Densities.—The allowable current densities which obtain in good practice are as follows: Busbars, switch blades, switch and instrument studs and other sections of copper, 1000 amp. per square inch; allowable density in plain clip contacts.

50 to 70 amp. per square inch; current density in laminated contacts, 250 to 400 amp. per square inch; density in bolted or clamped surface contacts, 100 to 200 amp. per square inch; density in contacts between screw studs and the inner surface of nuts screwing on them, 200 amp. per square inch, on surface of stud considered as a cylinder with a radius equal to that of the outside of the screw threads.

Busbars.—Where the amount of current exceeds 400 amp. busbars and conductors are made of flat, rolled, copper bars. These come in standard thickness of ¼ in., and in widths varying from 2 to 4 in. Where the cross-section of copper required exceeds that of a single bar, several bars are placed in parallel, they being spaced apart a distance equal to their thickness, or ¼ in. This form of busbar gives a considerable surface for

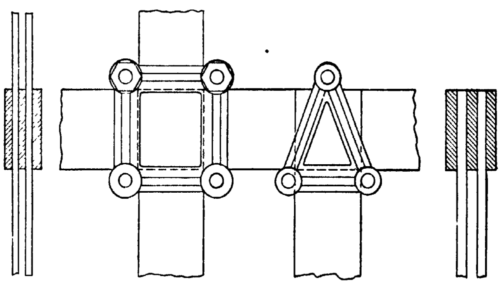

Fig. 27.—Busbars with clamp connections.

radiation and is convenient for making connections from the busbars to switches and instruments. Cross-connections are made of similar sections of copper bar which are interleaved between the busbars. In cases where a large number of cross-connections must be made in a limited space, the vertical or diagonal bars are bolted to the busbars with short iron bolts. The best practice, however, is to use iron clamps to connect the verticals and diagonals with the busbars. Fig. 27 shows sketches of busbars with the interleaved cross-connections held in place by clamps.

The busbars have considerable weight, and the switch studs should not be depended on to support them. It is usually better to carry the buses on supports which are fastened to the framework on which the switchboard is mounted. There are several forms of busbar supports. That shown in Fig. 28 is

satisfactory where a single copper bar only is required. For carrying several bars in parallel, iron brackets projecting from the rear of the board, their upper surfaces being of a trough-shaped section, which troughs are lined with slate or marble, make satisfactory supports.

Connections to switch studs are made as indicated in Fig. 29. The stud passes through holes made in the busbar sections and each bar, or section, is clamped between thin nuts, as indicated. The total area of contact that the stud makes with the bar and nuts must be sufficiently great to keep the current density within 200 amp. per square inch. This same condition must be fulfilled by the total area of the surfaces of the nuts in contact with the faces of the bars. If current densities are too high at any contact point, overheating will result.

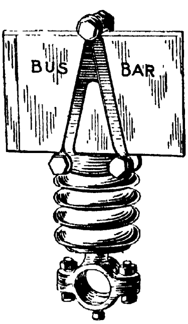

FIG. 28.—Busbar support, clamp type.

Figure 30 illustrates a simple diagrammatical method of determining the ampere capacity of bus required for any panel.[1] The method is as follows:

Make a rough plan of the entire board. The order of panels shown is recommended, it being most economical of copper and best adapted to future extensions.

To avoid confusion in the diagram keep on one side of board everything pertaining to exciter buses, and on other side everything pertaining to alternating-current buses.

Represent the exciter and alternating-current buses by single lines drawn across such panels as they extend over, and by means of arrows, indicate that portion of each bus which is connected to feeders and that portion which is connected to generators. Remember that "generator" and "feeder" arrows must always point toward each other, otherwise the rules which follow do not hold. Note also that the field circuits of alternating-current generator panels are treated as direct-current feeders for the exciter bus.

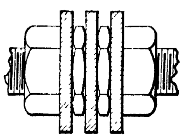

FIG. 29.—Switch stud connection to busbar.

On each panel mark its ampere rating, *i.e.*, the maximum current it supplies to or takes from the bus. For alternating-

[1] General Electric Co.

current generator panels the direct-current rating is the excitation of the machines.

Apply the following rules *consecutively*, and note their application in Fig. 30.

(*a*) Always begin with the tail of the arrow and treat "generator" and "feeder" sections of the bus separately.

(*b*) Bus capacity for first panel = ampere rating of panel.

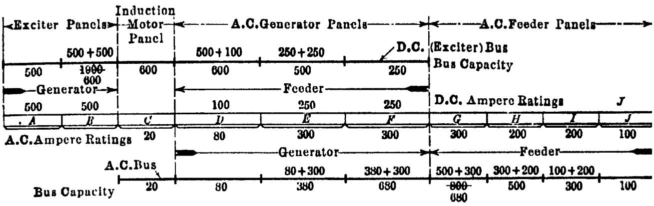

FIG. 30.—Diagram for computing busbar currents.

(*c*) Bus capacity for each succeeding panel = ampere ratin of panel plus bus capacity for preceding panel (see sums marke above the buses in Fig. 30).

(*d*) For a panel not connected to a bus extending across it use the smaller value of the bus capacities already obtained fo the two adjoining panels (see exciter bus for panel *C*).

(*e*) The bus capacity for any feeder panel need not exceed th maximum for the generator panels (see alternating-current bu

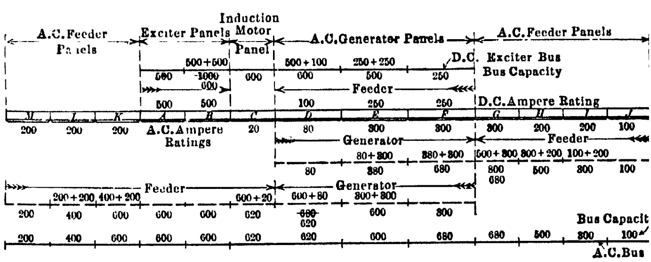

FIG. 31.—Diagram for computing busbar currents.

for panel *G*) and *vice versa* (see exciter bus panel for panel *B*) Hence the corrections made in values obtained by applying rule (*b*) and (*c*).

The arrangement of panels shown in Fig. 30 is the one whic is mostly used. The above method may, however, be applie to other arrangements, one of which is shown in Fig. 31. Her

the generators must feed both ways to the feeders at either end of the board, so that in determining alternating-current bus capacities it is necessary to first consider the generators with the feeders at one end, and then with the feeders at the other end as shown by the dotted alternating-current buses. The required bus capacities are then obtained by taking the maximum values for the two cases.

Where the cross-section required for the busbars progressively diminishes, from the point of the maximum current flow as the bars pass along the board, the number of individual bars required to make up the busbars becomes reduced, which means that some of the individual bars will be shorter than others. For instance, in Fig. 30 there might be three bars run across the back of panel *C* and *D*, one of the bars ending at the right hand edge of panel *D*. The other two sections would continue along behind panel *E*, and one of these would end at the right hand edge of panel *E*, the remaining bar running across the rear of panel *F* and there ending.

Switchboards should be made as simple as possible and attempts at excessive flexibility should be avoided. If sufficient switches and connections are provided to perform the ordinary routine of station operation, no advantage is gained by providing for extraordinary and sporadic conditions.

Knife switches should always be connected with the handles turned upward so that gravity will then tend to open and not shut them. The switch connections to busbars should be made so that when the switch is open the blades will not be charged. The busbar connections, therefore, should be made to the switch clips with which the switch blades contact when the switch is closed.

The spacing apart of busbars varies, of course, with the potentials. For exciter potentials, that is up to 250 volts, the busbars should be, approximately, 4 in. apart and no bare conductors, of opposite potential should come closer to each other than 2 in. For 2300 volts, alternating current, the busbars should not be located on the switchboard at all, but placed on supports which are carried on the top, horizontal brace rods, as shown in Figs. 50 and 51. The distance apart of the bars should be at least 8 in. Under no circumstances should potentials, higher than the exciter voltage be allowed on the switchboard itself.

A pilot lamp should be placed on each panel of the board, and so connected on the exciter panels that the lamp is lighted when each main switch is closed. On the main generator panels, the pilot lamp should be connected to the field switch so that it will be lighted when the field of the main generator is energized. In this way, the exciters or generators which are in use, or which are not disconnected from the circuit, may be seen at a glance.

Storage batteries are sometimes installed to insure continuous supply of exciting current. These are connected across the exciter busbars and provided with end cell switches so that the number of cells in series may be varied. The battery "floats" across the busbars and in case of accident to the exciters, or the circuits from them to the switchboard, the exciter current is supplied by the battery until the exciters are again put into service. This arrangement is an excellent one when motor-driven exciters only are used. The battery furnishes sufficient exciting current to start the plant and bring the motor-driven exciters into service after which the battery always stands ready to take the load in case of stoppage of any of the motor-driven units.

Switchboard Devices.—The instruments usually required to measure and control the energy of an electric generating station are:

1. Voltmeters, both direct and alternating current.
2. Amperemeters, both direct and alternating current.
3. Wattmeters, (alternating current).
4. Power-factor meters, (alternating current).
5. Frequency meters, (alternating current).
6. Ground detectors, (direct and alternating current).
7. Synchroscopes for showing when a generator is in synchronism with the operating units and ready to be connected to the busbars.

The *switches* are of various forms and comprise:

(*a*) Plain knife switches for circuits of 500 volts or less.

(*b*) Manually operated oil switches for circuits of 2300 volts or greater.

(*c*) Automatically controlled oil switches which are set to open under certain predetermined conditions of current or voltage.

(*d*) Distant-control switches, operated by a mechanism, which latter is set in motion, manually, at some point located at a distance from the mechanism itself.

(*e*) Disconnecting switches. These are large knife or horn switches, put in the main line, but never opened when current is passing over them. They serve to shift connections or disconnect certain parts of the line for emergency conditions.

(*f*) Plug switches for connecting voltmeters, synchroscopes and other instruments to any desired circuit.

(*g*) Ammeter switches for connecting an amperemeter to any phase, when series transformers are used.

Potential Transformers.—These are used whenever the voltage of a circuit exceeds 750 volts. The primary circuit of the transformer receives the high voltage of the line, and the instruments receive the lower voltage of the secondary winding of the transformer. The voltage of the transformer secondary is always exactly proportional to the voltage of the line.

Current Transformers.—These are used like the potential transformers, to obtain a small current from the line to the instruments which is always exactly proportional to the current in the line, so that a measurement of the secondary current is equivalent to a direct measurement of the line current.

Motors, or solenoids, for operating oil switches, which are set in motion by closing a small switch; either a manually operated push button or an automatic relay switch. The motor, or solenoid, is mechanically connected to the moving parts of the oil switch and, when set in motion, opens, or closes, the switch.

Automatic Relay Switches.—These are very small switches provided with solenoid magnets which latter are usually connected to the secondary circuit of a series transformer. Therefore, changes in current in the main line produce proportional changes in the current through the solenoid and, by proper adjustment, the relay switch is caused to work automatically and close the circuit to the motor, or solenoid, which operates the main switch.

Measuring Instruments may be generally classified as direct-current and alternating-current. For direct current, the best and most used movement is the D'Arsonval, which consists simply of a permanent magnet, having between its poles a movable coil carrying the current to be measured, or a known, shunted portion thereof. Inside of the moving coil is a soft iron core used to reduce the air gap between the magnet poles. When this coil is energized by the current to be measured, it induces a field around the coil which, thereby, has a force set up in it tending to place itself parallel to the flux of the magnet. The move-

ment is opposed by a spring. This type of direct-current instrument has always been considered the standard, the only disadvantage being the tendency for a neighboring direct current, if short-circuited, with consequent high-current flow, to weaken the permanent magnet. This may be obviated by a modification of the instrument in which the stationary element is an electromagnet instead of a permanent magnet. The use of such an instrument, however, is not necessary except for use in railway work or in large central stations supplying large amounts of direct current for lighting purposes. Either of these types of instruments indicate polarity, whereby it may be observed whether the exciters or generators have been reversed, in shutting down.

The dynamometer and magnetic-vane types may be used either on alternating current or direct current, but are principally used on the former. The dynamometer type has in series, a stationary coil and a movable coil, the latter carrying the pointer. These coils tend to place themselves parallel. It is a rather expensive type on account of its construction but, otherwise, is most satisfactory.

The magnetic vane is a modification in which the moving coil is replaced by a vane of aluminum placed on the instrument spindle, at an angle, which vane will try to place itself parallel to the magnetic field of stationary coil. Theoretically, this instrument is not as accurate as the dynamometer type owing to the presence of the vane which introduces a small error due to frequency changes, but for commercial work it is satisfactory and the error is negligible.

The induction instrument is, essentially, for alternating-current circuits and works on the well-known principle of the induction motor. It uses a polyphase field which tends to cause rotation of a conducting disk. In an induction wattmeter there are two coils, one connected across the busbars, the other in series with the current. Due to the rotating field set up by the phase displacement of the two coils, the disk tends to rotate. In an ammeter or voltmeter, this polyphase field has to be produced by a so-called "split field." This is provided by making two parallel circuits, one with reactance and the other with resistance in series.

An alternative method is that used in the shaded-pole induction motor and is obtained by winding the single-phase coil on a

core which is practically split in half, one half of which contains a short-circuited copper winding.

The induction instrument has numerous disadvantages due to the fact that it is affected by frequency, temperature variations and wave form. Its greatest advantage is that its scale may be made much larger than is possible with other types.

Next in consideration is the shape of instrument. There are two general forms, the round pattern and the horizontal edgewise. For neatness and uniformity on a switchboard the consensus of opinion favors the horizontal edgewise type. Its only disadvantage is the curvature of the scale and possibility of glaring high lights, but this is more than offset by the use of a vertical spindle and its resultant small friction. The round pattern instrument has a flat glass, but the spindle is horizontal with the attendant difficulties of keeping it properly aligned and adjusted in the jewel bearings.

Instrument Scales.—The scales on indicating instruments should be fixed as follows: For ampere meters, the maximum current which they will have to indicate, plus 20 per cent. should be, approximately, the maximum reading on the scale. The greatest current should be taken as the guaranteed overload current which the generator can deliver per phase. After adding 20 per cent. to this maximum amount the standard instrument having a scale nearest this computed value is the one to be selected. Voltmeter scales should read the normal operating voltage, plus, approximately, 40 per cent. Wattmeter scales should be selected to read values equal to the maximum ammeter-scale value, multiplied by normal voltage value for direct current or for single-phase current.

Scales which extend somewhat further than those computed by the foregoing means may be used to advantage. The normal currents and voltages on full load, should move the needle over about two-thirds the scale.

Wattmeters.—Nearly all commercial polyphase watt-hour meters operate on the induction principle, and in them is combined the well-known two-wattmeter method of measuring three-phase power.

The three-phase wattmeter comprises in reality two wattmeters, the moving parts of both being placed on the same spindle and so arranged that their effects are cumulative. The standard three-phase meter comprises two circular disks placed

on the same shaft. Two potential coils and one current coil are placed over each disk. The induced currents in the disk, which are proportional to the pressure and to the current in the potential and current coils, cause rotation of the discs and the speed of rotation is proportional to the watts that pass through the instrument. The shaft is geared to a counting mechanism which records the output of the circuit to which the meter is connected. For accuracy, it is necessary that the friction of the moving parts be reduced to the least practicable value. The bottom pivot of the shaft which supports the weight of the moving parts, on which practically all the friction is set up, is made of some precious stone having extreme hardness, usually a sapphire. In order to prevent the meter from speeding up and over-running, a magnetic brake is provided which consists of permanent magnets, the poles of which project over the surface of each disk near its periphery. As the disk rotates between the poles of the magnet, local currents are induced in the disk which produce a magnetic drag and this drag increases with increase in speed, being proportional, approximately, to the speed.

Synchroscopes.—The synchroscope, or synchronism indicator, is used to show synchronism of generators which are started up and are to be switched on to the station busbars.

Figure 32 shows one standard form of the instrument. The pointer of this instrument moves around a dial—like the hand of a clock—and the angle of the pointer's displacement from the vertical position is a measure of the angle of phase difference between the two sources of electromotive force to which the device is attached. If, therefore, the incoming machine is running too fast, the pointer rotates in one direction, and if too slow, in the opposite direction.

Coincidence in phase is shown when the pointer remains stationary in a vertical position and indicates that the incoming machine should be thrown in. A complete revolution of the pointer indicates a gain or loss of one cycle in the starting machine as compared with the running machine.

The synchronism indicator is a motor whose field is supplied single-phase from one of the machines to be synchronized, and its armature from the other. The armature carries two coils placed at a large angle to each other, one supplied through a resistance, the other through a reactance. This arrangement

generates a rotating field in the armature, while the stationary field is alternating. The armature tends to assume a position where the two fields coincide when the alternating field passes

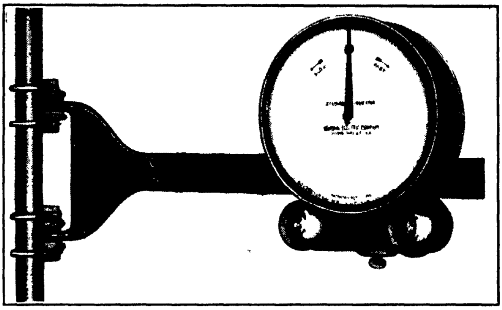

FIG. 32.—Synchronism indicator on swinging bracket.

through its maximum; hence, the armature and pointer move forward or backward at a rate corresponding to the difference of

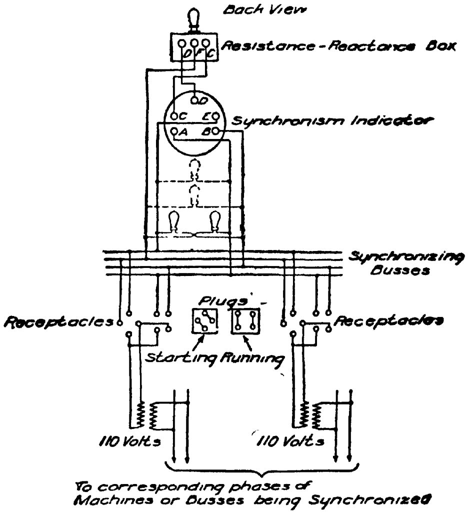

FIG. 33.—Connections for synchroscope.

frequency, and the position when stationary depends on the phase relation. When the machines are running at the same frequency and in phase, the pointer is stationary at the marked point.

There are, of course, several ways of connecting the instruments. Figs. 33 and 34 show the usual methods. They are always connected to the circuit through plug switches, and two plugs are required, one the "starting" plug which is for connecting the machine being synchronized, to the instrument; the other the "running" plug which is used to connect the instrument to the busbars. The cross-connections of these two plugs are shown in the figures.

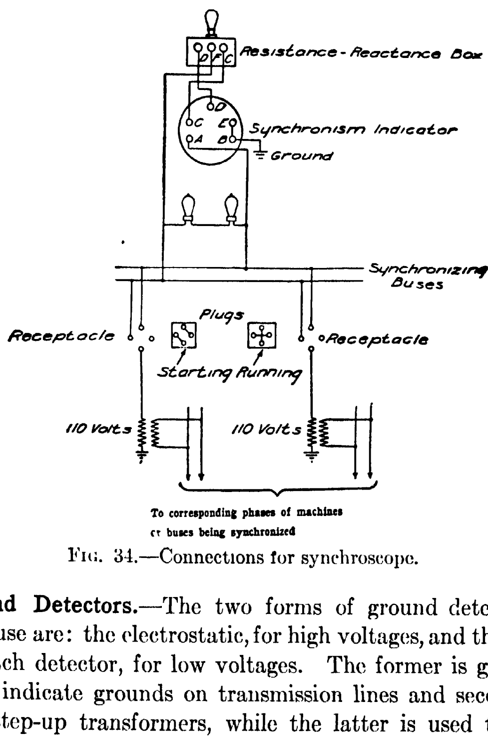

FIG. 34.—Connections for synchroscope.

Ground Detectors.—The two forms of ground detectors in general use are: the electrostatic, for high voltages, and the lamp-and-switch detector, for low voltages. The former is generally used to indicate grounds on transmission lines and secondaries of the step-up transformers, while the latter is used to show grounds in the exciter circuits and generator fields.

The electrostatic detectors work on the principle of the attraction which exists between metallic surfaces which are electrically charged. No current flows through the instrument. The three-phase detector is made up of three segmental sections of thin aluminum plate which are supported inside the instrument case, and insulated from it. Spaced at 120° apart, inside the instru-

ment case, are three movable flat vanes, also made of thin sheet *aluminum.* These latter are pivoted and free to rotate through a *comparatively small angle. Each has a needle attached to it, the three needles pointing radially toward the center of the case.* The pivoted vanes are electrically, as well as mechanically, connected with the instrument case, and the case is connected with the ground. The insulated, fixed vanes are each connected to one leg of the system. This construction is as shown in Fig. 35. Obviously, if there is a ground of one of the phases, the aluminum disk to which it is connected will have the same potential as one side of the pivoted disk and there will be no attraction between these two disks. The next adjacent fixed disk connected with another leg of the system will, therefore, exert an unbalanced pull on the other side of the pivoted vane so that the latter will move and cause a deflection of the pointer attached to it. Usually, the connections are made through high-resistance rods of graphite so that in case the end of the vanes should be bent, making electrical contact with adjacent ones, the current flow would be limited to a negligible amount. For high potentials, say 15,000 volts and above, the instrument should not be connected directly to the line but through small condensers which are provided for the purpose. It is not customary to mount these instruments on the surface of the switchboard panels. They are usually placed above the totalizing panel on an iron bracket. This is due to the fact that they carry high potentials.

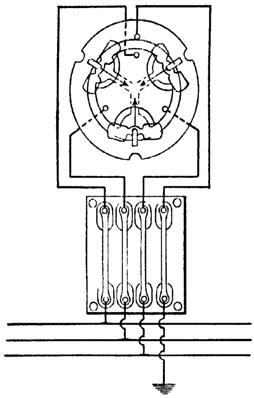

FIG. 35.—Electrostatic ground detector.

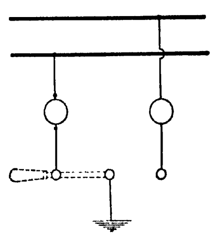

FIG. 36.—Lamp ground detector.

The lamp ground detector is made as indicated in Fig. 36, a single-pole double-throw switch and two lamps being all the apparatus required. As shown, the middle point of the switch is connected with the ground, while one lamp is connected between a busbar and a switch clip. When a switch is thrown

into one clip, it connects the lamp, and the busbar with which it is connected, to the ground. There is no circuit through the *lamp unless the other busbar is grounded. Hence, the lighting of one of the lamps indicates that the busbar attached to the* other lamp is grounded. Usually, small lamps set in "bull's eyes" on one panel of the exciter board, and a small knife switch are installed to make up these ground detectors.

Rheostats.—Rheostats are simply variable resistances connected in series with the field windings of dynamo-electric machines, and by means of which the voltage of the machines may be varied at will. The variation is effected by turning a small handwheel which moves an arm carrying a contactor that changes the amount of resistance in the circuit, as it moves over contact points with which it coöperates.

For small generators, such as exciters of less than 250-kw. capacity, the rheostat is small enough to mount on the rear of the board. The operating shaft passes through the panel and the handwheel is fastened on it, on the front of the board.

Large rheostats are mounted on the iron wall-braces above the switchboard, or, where possible, are located below the floor underneath the switchboard. In these cases, the handwheel at the front of the board has a shaft attached to it, which passes through the panel and at the rear end of the shaft is a small sprocket wheel. A corresponding sprocket wheel is fixed on the pivot of the rheostat, about which the contacting arm revolves. The two sprocket wheels are connected by a sprocket chain, and by this means, movement of the handwheel causes rotation of the arm.

Rheostats must have a certain maximum resistance and current-carrying capacity which depend on the characteristics of the generators they control. For this reason, they are always furnished by the manufacturer of the generator as a part of the generator equipment, and are shipped to the switchboard builder who mounts them with the other parts of the switchboard.

It is advisable to require that the field rheostats for all electrical machinery be arranged for one contact arm only. Where several contact arms are used in parallel, failure of one to make contact with its contact point will cause the total current to flow through the other, or others, and in this way, overload the resistances which still remain in circuit. This usually results in the over-

loaded sections of the rheostat burning up, and it becomes necessary to shut down the generator until a new rheostat can be substituted.

When automatic voltage regulators are used, the rheostats must be proportioned to accord with the conditions imposed by the voltage regulator. Usually, the requirement is that the maximum resistance of the rheostat be great enough to reduce the voltage of the generator to 50 per cent. of the normal.

Relays.—Alternating-current relays may be generally divided into the overload, reverse power, over-voltage, and no-voltage types, and also into instantaneous and time-limit subdivisions. Where direct current is available for operating, it is advisable to use circuit-closing relays so that the oil switches, or other devices, may be equipped with direct-current releases operated by an independent voltage impressed through the contacts of the relay. Inasmuch as alternating-current relays are generally used in connection with current and potential transformers, the use of the direct-current tripping system does not require additional current transformers, and does not unbalance those in use. The inherent advantages and positive operation of direct-current solenoids make their use desirable.

The most generally used relay is the *straight overload*, which, in the simplest construction, consists of a plunger operated by a coil in series with the current transformer in the circuit to be protected. When a predetermined current value is reached, the solenoid action will lift the plunger which in turn closes an electrical contact. It is generally required that these relays have an inverse time limit. For such service, a small leather bellows is compressed by the upward movement of the plunger, and air escapes through an adjustable needle valve. This produces an inverse time-limit effect, as the magnitude of the current, fixes the speed with which the bellows is compressed. A definite time limit may be obtained by the addition of small spring interposed between the plunger and the bellows. The plunger compresses the spring, which, in uncoiling, operates the bellows, so that a definite time limit of operations is obtained.

There are various and more costly methods of obtaining these results in a more exact manner, such as the principle of escapements, rotation of disks by induced currents, fuse blowing, etc., but for most cases, the simplicity and economy of the plunger and bellows type of relay satisfactorily adapt it for the purpose.

The most commonly known *reverse-power relays* are those used directly on a line to operate if a reversal of power should occur, and the relays used in circuit with the power transformers to protect the system from internal troubles of the transformers when there is more than one transformer bank in multiple. This form of relay has each pole made up of two coils, and each coil is connected to current transformers which latter are connected to opposite sides of the transformer circuits. Under normal conditions of operation, the effect of the two relay coils on each other is neutralized, but on occurrence of trouble in the transformer, when power flows into it from both directions, the current in one coil of the relay reverses, so that both coils then tend to lift the plunger and trip the oil switches in both circuits of the transformer.

The best type of reverse-power relay for power lines, is that constructed on the dynamometer principle. The relay then acts as a wattmeter, having both current and potential coils. Under normal directions of power supply, the relay tends to remain open but on reversal there is a tendency for rotation in the other direction, as in the indicating wattmeter, which motion closes a contact operating the main oil switch. These relays may be made to operate on 1 amp. reversal at 110 volts, 3½ amp. at 20 volts, and 10 amp. at 5 volts, the curve of operation being hyperbolic between these values. A change of power factor from 80 to 15 per cent. affects these current values only 10 per cent. These relays cannot operate on overload or short-circuit in the normal direction.

Another reverse-power relay is the plunger type with current and potential coils on the same plunger. The coils are so proportioned that with full potential, the relay will operate on 1 amp. reversal of power. This relay is not suitable for protection of two parallel feeder lines on account of its tendency to operate on overload when the voltage is reduced. As the lines are electrically connected, a short-circuit in one line will cause the potential to drop on both, and the probability is that both relays will operate, one on reversal and the other on overload. An arrangement for eliminating this effect is to use two such relays, connected mechanically by a walking beam which allows one relay to operate at a time, but not both. This, however, involves complications in case only one line is operated at a

time. In this case, the oil switch must have auxiliary switches to reconnect the other relay.

For hydro-electric generating stations, nearly all abnormal conditions can be taken care of by the use of straight overload relays, with selective time settings to give the proper sequence of operation of the switches, and reverse power relays.

Current Transformers.—All alternating-current instruments, for circuits above 750 volts, should use current and potential transformers.

The current transformer is a plain transformer with primary and secondary coils and having an iron shell between the windings. Manufacturing standards have fixed 5 amp. as the secondary current of all current transformers for normal full load through the primary circuit, so that 5 amperes is the current rating of all instruments connected thereto for full scale deflection.

It is erroneous and misleading to speak of current transformers having a rating in watts. The rating should be fixed according to the character of the load. The ratio of transformation does not hold good at all current values. There is a critical point on the regulation curve where the ratio is exact, but for higher or lower values of current this changes. The error should not exceed ½ per cent. at 50 per cent. of normal load; 1 per cent. at 25 per cent. load and 2½ per cent. at 10 per cent. load.

According to the instruments connected to the transformer, certain errors are permissible, the case for most careful consideration being that of watt-hour meters.

The commercial means of rating current transformers in permissible volt-amperes, is not specific, because the volt-amperes vary with the current flowing, but for convenience and as a mode of comparison, it is assumed that 5 amp. is the current on which the rating is based. As the primary ampere-turns increase, or as the primary current increases, the capacity of the transformer will increase and *vice versa*, so that if with 5 amp. in the secondary winding, the capacity of the current transformer is 30 volt-amperes and a primary current corresponding to 3 amp. in the secondary is flowing, the volt-ampere capacity of the transformer will be only three-fifths of its rating. Further, it should be noted that the ability of a series transformer to maintain its ratio of transformation varies slightly, with the frequency.

The secondary of current transformers should never be open-circuited. The primary magnetomotive force of a current

transformer, is made up of an exciting, and an active magnetomotive force. As the secondary load increases, the ratio of the transformer will diminish and the secondary current will decrease. As the secondary current decreases, the active primary *magnetomotive force opposing it will decrease, and the exciting magnetomotive force will increase proportionately. If the* secondary current becomes zero, then the whole primary magnetomotive force exerts itself as exciting magnetomotive force and a destructive voltage results. The secondary open-circuit voltage will rise, on the average, to between 800 and 1000 volts, and transformers of good design should be able to stand this pressure from 5 to 10 min.

As a rule, current transformers are air-cooled up to about 15,000 volts but above this value the transformers should be oil-cooled and immersed in iron tanks.

Voltage test of current transformers should be between two and one-half and three times the normal rated voltage between primary and secondary and between primary and ground. The test between secondary and ground may be approximately 1500 volts in all cases.

Potential Transformers.—In reducing primary voltage to a measurable value it is necessary to employ potential transformers of a known and constant ratio. These transformers are rarely over 200 watts in capacity which output serves all commercial needs for instruments and meters. It has been generally accepted that 100 or 110 volts shall be the secondary voltage so that the ratio of transformation is 20, 40, 60, 120, etc., respectively, as the primary voltage is 2200, 4400, 6600 or 13,200.

While current transformers can be built so that the identical transformer is suitable for all commercial frequencies, potential transformers can not be so designed. These are widely different for, say, 25 cycles and 60 cycles. The former are much larger transformers and require more iron for the magnetic circuit.

It is advisable to place fuses in both the high-tension and low-tension circuits of potential transformers. Due to the low voltage, the secondary fuses can be standard enclosed fuses, of such a capacity that the transformer is absolutely protected from overload and leakages to ground which might become serious. Fuses should also be placed in the primary. Because of the high voltages and correspondingly negligible current, these fuses can serve no purpose other than protection in case of short

circuits. These fuses can best be of the expulsion type, mounted apart from the switchboard when the voltage exceeds 2300. Voltages of 2300 and under allow the use of enclosed fuses.

Transformers may be safely built air-cooled, up to and including 6600 volts but above that it is advisable to use oil-cooled units. Potential transformers are built for all commercial voltages up to 33,000 volts. Above this value it is advisable to do all metering on the low-voltage side of the system as instrument transformers of such rating become abnormally expensive; for instance, a potential transformer for a 60,000-volt circuit costs, approximately, $400.

Equipment of Panels.—The instruments are usually mounted on vertical panels of slate or marble, the panels being supported on an iron framework.

The panels are equipped for the machines or circuits they control. A board usually comprises as the minimum equipment, the following:

1. Exciter panels.—There is usually one panel for each exciter, unless the exciters are small in which case, two may be served by one panel.

The equipment for each exciter comprises:

One amperemeter.

One voltmeter.

One main switch.

One plug switch for voltmeter.

One pilot lamp.

One exciter field rheostat.

Also, there is on one of the panels, a ground detector which is made up of a single-throw, double-pole switch, connected with a pair of lamps. If the exciters are motor-driven, it is preferable to mount the handle of the motor starter on the same panel as that of the exciter driven by the motor.

2. Generator Panels.—One panel for each generator. On each one is placed:

(*a*) Operating handle for controlling the main oil switch.

(*b*) One amperemeter for alternating current.

(*c*) One amperemeter switch—3 points.

(*d*) One voltmeter for alternating current.

(*e*) One plug switch for voltmeter—4 points.

(*f*) One plug switch for synchroscope.

(*g*) One amperemeter for direct current, to measure the exciting current.

(*h*) One generator field rheostat.

(*i*) One generator field switch, with field discharge resistance.

(*j*) Two potential transformers (not mounted on the board).

(*k*) Two series transformers (not mounted on the board).

(*l*) One pilot lamp.

3. Totalizing Panel.—On this are mounted the instruments which show the total output of the station. Its usual equipment comprises:

(*a*) One amperemeter—alternating current.

(*b*) One amperemeter switch—3 points.

(*c*) One indicating wattmeter.

(*d*) One recording watt-hour meter.

(*e*) One frequency meter.

(*f*) One power-factor meter.

(*g*) Lighting-circuit switches.

(*h*) Operating handle for oil switches to station transformers (*i.e.*, small transformers from which current is obtained for station motors).

(*i*) Overload relay for station oil switch.

(*j*) Electrostatic ground detector, usually mounted on an iron bracket above panel.

(*k*) One synchroscope. } These two instruments usually on a
(*l*) One voltmeter. } swinging bracket at end of panel.

(*m*) Operating handle of main oil switch, connecting busbars with line to step-up transformers.

(*n*) Overload relay for main oil switch.

Sometimes, several lines lead from the busbars to transformer banks, in which case, additional oil switches are required, and these are mounted on panels called "feeder panels."

Framework.—Large, elaborate switchboards are usually supported on frames of angle iron, the sections being 2 by 3 in., the panels resting against the narrow web and the two wide webs being bolted together at adjacent sections, as indicated in Fig. 37. These vertical angles are fastened at the bottom to a horizontal channel bar which latter is set in the floor of the power station, or switchboard gallery, as shown in the figure. Most switchboards, however, are mounted on pipe framework made up of vertical pieces of standard wrought-iron pipe 1½ to 2 in. diameter. A complete line of malleable-iron fittings has

been developed by various manufacturing companies, by means of which the panels, busbars and all accessory portions of the switchboard may be easily attached to the vertical pipe supports.

The pipes are usually fastened to the floor by standard floor flanges, into the sockets of which the pipes are screwed. The board is braced in its vertical position by horizontal wall braces which run from the top of the board to the wall in the rear, one end being connected to the vertical pipe support by means of Tee fittings, the other end being fastened to the wall by a standard floor flange or a wide angle plate into which the pipe is screwed and which is fastened to the wall by means of an expansion bolt, passing through the flat section of the wall

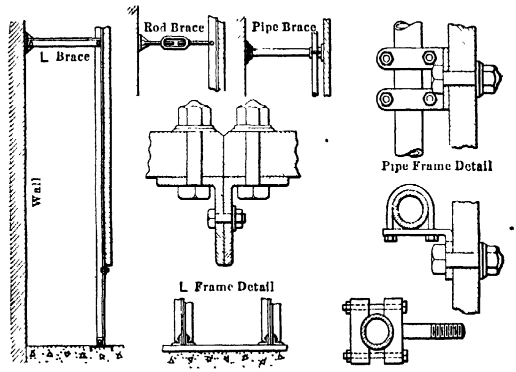

FIG. 37.—Details of switchboard framework.

plate. A few of the details of this pipe framework are shown in Fig. 37.

Material of Panels.—At the present time there are two materials which are universally used for switchboard work, namely, slate and marble. Slate must be carefully selected for insulating qualities as well as strength, and when used in its natural color must be selected for appearance as well. The three varieties of the finished switchboard product used are natural black slate, dull black marine-finished slate and black enameled slate

There are several varieties of marble suitable, the most serviceable being blue Vermont marble, pink and gray Tennessee, white Italian and white Vermont.

Owing to its greater strength, slate is recommended for all switchboard work when the potential directly on it does not exceed 1200 volts for natural black slate and 650 volts for dull black marine-finished slate. Above these values, marble must be used.

The following gives the characteristics of the various materials arranged in the order of their mechanical strength beginning with the strongest.

Natural Black Slate.—Consists of Monson Slate in its natural color which is rubbed with oil bringing out its rich black appearance. It is not easily soiled and needs only an occasional rubbing with oil to keep it in good condition. It is the best material for switchboards of any class, where the voltage limits given are not exceeded. It is less expensive than marble or black enameled slate, but slightly more expensive than the dull black marine-finished slate.

Dull Black Marine-finished Slate.—Is a purple slate to which is applied a dull black lacquer giving an appearance closely resembling natural black slate. The slate itself before being lacquered, does not have a uniform color and the coating of lacquer may be used to cover an inferior grade of slate with metallic veins which would be apparent in the natural black variety.

Black Enameled Slate.—Is the same grade as the dull black marine-finished but is finished with black japan, baked and rubbed down to a highly polished surface. On account of this polish it is easily marred and reflects light into the eyes of the attendant. This material has practically ceased to be used.

Blue Vermont Marble.—Consists of marble in its natural color. It is found in various shades and markings. It has better insulating qualities than slate but has not as great strength and should not be used where it would be subject to heavy jars. It absorbs oil and grease, so that it does not present a clean appearance after any considerable age. It is also difficult to match existing panels in color when ordering additions.

White Italian Marble.—Is imported and consequently, delivery is delayed accordingly. It varies slightly in shades, absorbs grease and oil and easily becomes discolored in a short time.

Tennessee Marble.—Can be obtained in either pink or gray shades. It has the same general characteristics as the other marbles, but does not so easily become disfigured with age.

White Vermont Marble.—Resembles the imported stock except that it is practically a pure white, not attractive in appearance even at first, and is entirely too difficult to keep clean.

The width of panels varies from 16 to 24 in., and the usual height is from 84 to 96 in., 90 in. being now generally standard.

The weight of switchboards varies from 300 to 450 lb. per lineal foot.

Plug Switches.—For connecting instruments to different circuits, plug switches are used. These are made up of pairs of tubular metal sockets, each socket provided with a terminal which passes through the panel and is electrically connected with its allotted circuit or instrument terminal. A hand plug, having on it four projecting lugs which are of proper size to fit into the receptacles, and so spaced on the handle base that they simultaneously slide into the receptacles, constitutes the switch. The

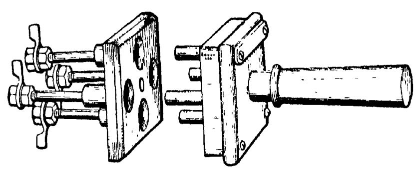

FIG. 38.—Plug switch and receptacle.

plugs are interconnected in any desired manner, by cross-connections in the handle base. Fig. 38 is a view of a plug switch and receptacle.

Ammeter Switches.—These are small rotating switches by means of which the three sets of secondary connections from series transformers in a three-phase circuit may be connected to one amperemeter, the connection being shifted at will, by means of a switch, to indicate the current passing through any phase of the system. It differs from the plug switch in that the parts are so interconnected that in the transition from one phase to the next the secondary circuit of the series transformers are never opened but are all short-circuited during the movement of the switch, and the transformers on those phases which are not connected with the amperemeter are maintained short-circuited as long as the switch remains in that position. By using these switches, one amperemeter only, is required to measure the current flow in any one of the three phases.

Field Switches.—The field winding of any generator, com-rising as it does, a large number of turns of wire around iron ores which form part of a magnetic circuit, has a very high ıductance, and if the circuit through which current is supplied o these windings is suddenly opened, the reverse voltage, or 'kick," from the sudden collapse of the magnetic field may be reat enough to puncture or injure the windings. In order to pen the field without producing this inductive voltage, a field witch is used which is provided with an auxiliary contact, and rom this contact to one side of the field circuit is connected a esistance The auxiliary contact is so disposed that the switch lade does not touch it when the switch is losed and, therefore, there is no circuit hrough the resistance. When the switch is pened, the blade touches the auxiliary con-act before it leaves the main contact. Fur-her movement of the switch interrupts the ircuit from the source of supply of field cur-ent, but maintains the connection of the esistance across the field circuit. The field s, therefore, free to discharge through this esistance and, thereby, prevent the pro-luction of excessive inductive "kick." The ırrangement is indicated, diagrammatically, in Fig. 39.

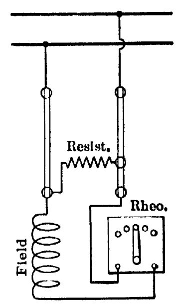

FIG. 39.—Field switch connections.

Disconnecting Switches.—Disconnecting switches above 2500 volts, are mounted on porcelain insulators which in turn are generally mounted on steel bases. For 2500 volts and below, the ordinary knife switch mounted on a marble base, suffices. For voltages above 2500, the switch and insulators may be arranged vertically or horizontally, and to open up, or down, as the case requires. They may be equally serviceable outdoor or indoor, and the studs may be either front-connected or arranged with the stud passing through the insulator and projecting through the steel base, giving a back-connected effect. If desired, the insulators can be mounted on pipe framework by means of clamps instead of on flat steel bases. The latter arrangement is preferable, however, as it insures constant and perfect alignment of the contacts at all times and eliminates the possible variation caused by the slipping of an insulator on the pipe.

If the switch opens downward, or if the blade of the switch is parallel to, and in proximity to another part of the same conductor carrying current of opposite polarity, it should always be provided with "safety catch." This is a small device attached to the upper stud of the switch which insures its being closed unless the operator trips the catch with the operating hook when preparing to open the switch.

Air-break Switches.—Air-break switches can be made with any reasonable number of poles and to operate under conditions of overload, underload, reverse current, or low voltage. The main, current-carrying brush should be of the laminated type and so arranged that in closing on the contact block a wiping motion is obtained, thus insuring a clean contact. In addition to the main contact, there should be an auxiliary metallic contact closing the circuit before the main brush, and opening after it does. Further, there should be a secondary contact of carbon, operating, in the same relative sequence to the auxiliary contact, so that in opening the circuit-breaker under load, the first break is made by the main brush, and the current is shunted through the auxiliary contact and the carbon contact, finally breaking the arc through the carbon contact, which sequence insures protection and obviates burning of the main brush. The reversed order of events occurs in closing the circuit-breaker, which condition tends toward the same result.

The heating of circuit-breakers, under load, is comparable to that of knife switches and they are subject to the same requirements.

Oil Circuit-breakers.—The principal advantage of oil switches is that they tend to open the circuit when the potential passes through zero.

The size of oil switches is fixed by the rupturing capacity under short-circuit conditions. To specify this in kilowatts is misleading, as the power factor of a system is a determining factor. It is, therefore, necessary to specify the capacity in kilovolt-amperes.

A test to determine these ratings can be arranged by means of two or more generators in parallel, all connected to the switch under test. The limiting capacity is found when the oil switch begins to throw oil. The first trial is made with one generator alone and if the switch successfully opens the short-circuit, the kilovolt-ampere capacity is increased by means of additional gen-

erators until the switch begins to throw oil, showing that the explosive tendency of the arc exceeds the quenching ability of the oil, at which current value the maximum rupturing capacity of the switch has been reached.

The rupturing capacity of a switch depends partly on the rapidity with which it is opened under short-circuit conditions. In the usual hydro-electric station, the reactance of the generators with their external connections, is such that the short-circuit curve is practically a straight line, the maximum current peak being, approximately, four times the normal and occurring within a half of the first cycle, after which it rapidly reduces, reaching the sustained short-circuit value of current in 20 cycles. For stations with less than 8 per cent. reactance between generators and their connections to the busbars, the momentary value of the short-circuit current reaches about fifteen times the value of normal current.

This abnormal condition can be greatly alleviated by the introduction of time-limit relays set to trip in not less than 2 sec. delay, after which interval the short-circuit current is diminished and the severity of the duty imposed on the intervening oil switch is greatly reduced. For relays set to trip in 2 sec. delay, the ratio between the maximum current at the time of switch opening and normal current, for stations with less than 8 per cent. reactance, is five times the normal current, and for stations with more than 8 per cent. reactance, is three or four times the normal.

Oil switches for systems having considerable generator reactance may be safely rated at 40 per cent. more rupturing capacity than those for stations where the reactance of the generators (including that of their connections to the buses) is less than 8 per cent. Similarly, a switch equipped with a time-limit relay, set to trip in not less than 2 sec. delay, can be rated approximately with 50 per cent. more rupturing capacity than one set to trip instantaneously, or as nearly so as the mechanical movement of the parts permits.

Oil switches can be arranged with all poles in the same oil container or in separate compartments, in which latter case the rupturing capacity of the switch is increased about 15 per cent. on account of the diminished fire hazard. The switches may be mounted on pipe framework or in cells or compartments. For stations above 15,000 kw., capacity, it is desirable to enclose the

busbars in separate compartments, and to mount the oil switches with each pole in a separate masonry cell. Such an arrangement minimizes the risk from fire and the expense is small in proportion to the total station cost.

For stations of 15,000-kv.a. capacity or less, it is better to place the oil switches in a row on a pipe framework or against the wall in the rear of the board. Hand-operated switches are controlled

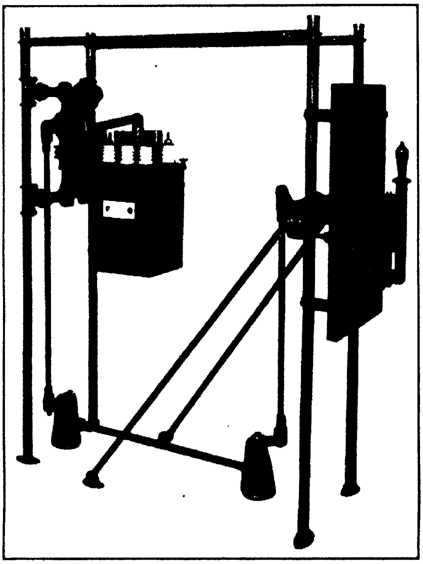

FIG. 40.—Hand-operated oil switch (with overload relay).

by handles mounted on the switchboard panels, and connected to the switch mechanism by means of bell cranks and clevises with pipe connecting rods, as shown in Fig. 40.

Remote-control Switches.—Remote control is of two kinds. The switches may be located at a short distance from the board and operated manually, there being some form of mechanical connection between the switch and the operating handle.

Where the voltages are great, say above 15,000 volts, and the switches become heavy and difficult to move, they are actuated by electrical energy, a small geared motor, or heavy solenoid being connected with the moving parts to operate them. Usually,

the motor, or solenoid, closes the switches and a heavy spring opens them. Electrically moved switches are controlled by small hand switches mounted on the switchboard which supply energy in the desired direction, to the motor, or solenoid. Generally, the operating current is taken from the exciter busbars. Where remote-control switches are used, they can be placed in any desired poisition regardless of the location of the switchboard

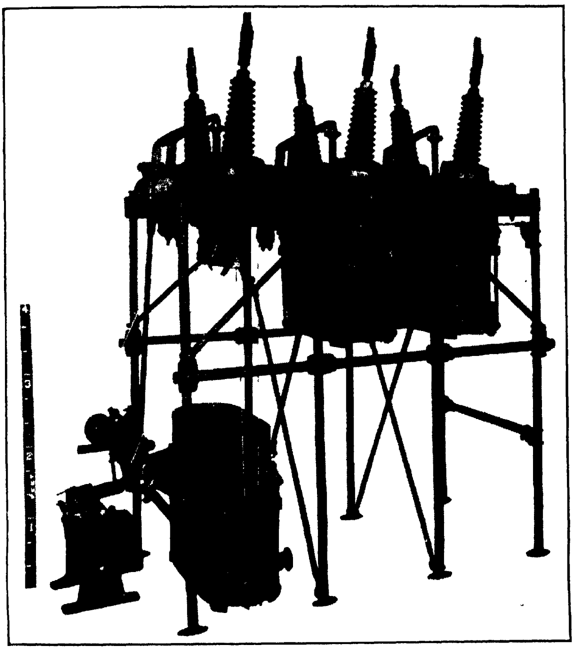

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FIG. 41.—High tension, triple-pole oil switch with tank-lowering pulleys and windlass. One tank removed.

itself, and considerable economy may be effected in running the connecting cables from the generators and the busbars to the switches. In addition, the apparatus can be concentrated with a saving of space, and in case of troubles from high potentials they are confined to the switches and switch compartments, which are usually in fireproof chambers, and removed from the operator and the rest of the power station.

Fig. 41 shows a solenoid-operated oil switch with one of the

tanks lowered. Fig. 42 is a picture of a motor-operated oil switch, with the tanks removed exposing the switch clips and contacts.

Oil switches should be tested dry, with a voltage applied between the "live" parts and the case, and between the live parts and the framework. The switch should stand an application of at least twice the normal operating voltage in either instance without flashing or breakdown.

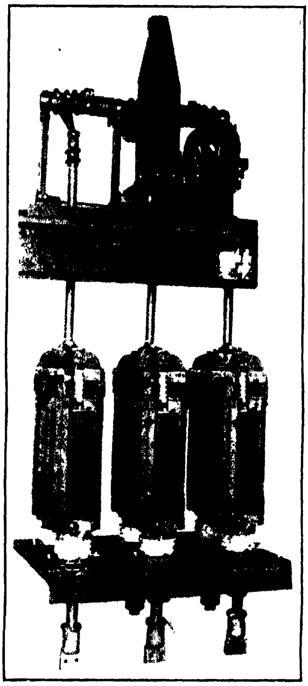

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FIG. 42.—Triple-pole, high-tension, motor-operated oil switch. Tanks removed.

Oil.—The oil used in cells of oil break switches, may be any good paraffin oil, free from moisture, provided it meets the following requirements: Flash point to be not under 180°C.; fire test not under 200°C.; specific gravity to be approximately 0.865. The evaporation must be negligible and it must be free from acids and alkalies.

Testing Facilities for Instruments and Relays.—The calibration of instruments being necessary from time to time, it is desirable to provide means for inserting standards in the circuits and, periodically, determining the accuracy of switchboard instruments, meters, and relays.

For the instruments and meters, the general method is to place the calibrating standards in series with the apparatus under test. For instance, all the instruments and meters on a generator panel are operated from one set of instrument transformers. Hence, a means of using calibrating terminals, which will allow the insertion of the testing instruments should be provided. For the current coils, these terminals each consist of two studs with thumb screws and a connecting removable link. The

studs must be provided with extra terminals for the connection of the leads to the current coils of the testing meter, after which the connecting link may be removed without open-circuiting the current transformer secondary. For two- or three-phase circuits, only two such calibrating terminals are necessary as this is the number of secondary leads from transformers to the panel.

The potential coils only of testing instruments need be connected in multiple with those in operation. This can best be accomplished by means of three studs with extra terminals. These studs should be wired in circuit with the secondary leads from potential transformers to the panel, and the leads from testing instruments can be connected to the extra terminals.

The testing facilities for instruments and meters can be, most conveniently, mounted on the rear of the switchboard.

The testing of relays involves more complicated equipment. The generally accepted method is by the use of a multipole, double-throw, knife-blade switch with blades extending in both directions at such an angle to each other that the switch makes contact on one throw before breaking contact on the other throw. This then makes it possible by one operation to entirely disconnect the relay from the current and potential transformers, short-circuit the current transformer leads and re-connect the relay to the test circuit. This circuit can best be obtained by use of a small voltage transformer of, approximately, 1 kw., giving 110 volts. A variable resistance is used in series with this transformer which controls the current flow. An ammeter with a 25-amp. scale should also be connected in series with the leads of the testing transformer. For a switchboard of considerable size it is desirable to have a relay test bus the entire length of the board. Only one relay can be tested at a time. It is, of course, undesirable to allow the instruments and meters to remain in the test circuit, for under such circumstances the watt-hour meters would record the power supplied by the testing current which would make the statistical readings inaccurate.

No well-defined method can be illustrated to cover all such provisions for relay testing, as each case should be considered on its own merits. The use of such a switch as that mentioned previously is merely a suggestion applicable in all cases. Periodical testing of protective relays is necessary to insure their reliability of operation.

Automatic Voltage Regulation.—The use of automatic, generator voltage regulators has become a necessity in plants subject to quick load fluctuations and is more necessary in small plants than large ones. These regulators maintain constant voltage on the busbars and obviate the necessity of manual control of the generator field rheostats.

The desired voltage is best maintained by an automatic device which rapidly opens and closes a short-circuiting contact across the exciter field rheostat. The rheostat handle is first moved until the exciter voltage is greatly reduced and the regulator circuit is then closed. This short-circuits the rheostat through contacts in the regulator and the voltage of the exciter and generator immediately rise. At a predetermined point, the regulator

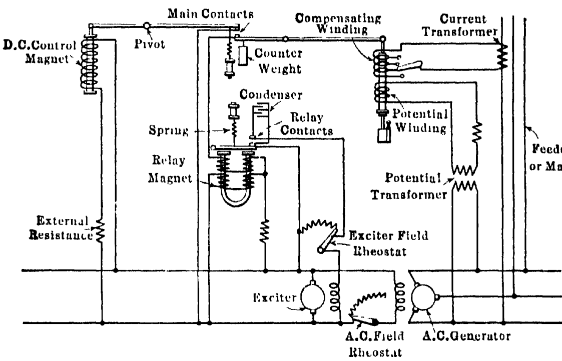

FIG. 43.—Elementary connections of Tirrell voltage regulator.

contacts are automatically opened and the field current of the exciter must again pass through the rheostat. The resulting reduction in voltage is arrested at once by the closing of the regulator contacts which continue to vibrate in this manner, and keep the generator voltage within the desired limits.

The regulation being effected entirely in the field circuit of the exciter, the system operates at the highest efficiency and eliminates the losses resulting from operating directly on the generator field. One automatic voltage regulator may control the voltage of a system operating two or more alternators in parallel by a suitable arrangement of equalizing rheostats.

For the total range of regulators from no load to full load the maximum travel of the only moving parts, namely, the vibrating contacts, is but $\frac{1}{32}$ in.

It should be noted that the most satisfactory voltage regulation is obtained by the operation of all exciters in multiple.

The A.C. control magnet is wound with both a current and a potential coil so that, if required, the voltage may be maintained at a remote point and allowance is made for line drop by a compensated adjustment. This portion of the main coil winding may be left out of circuit if it is only desired to maintain constant voltage on the station busbars.

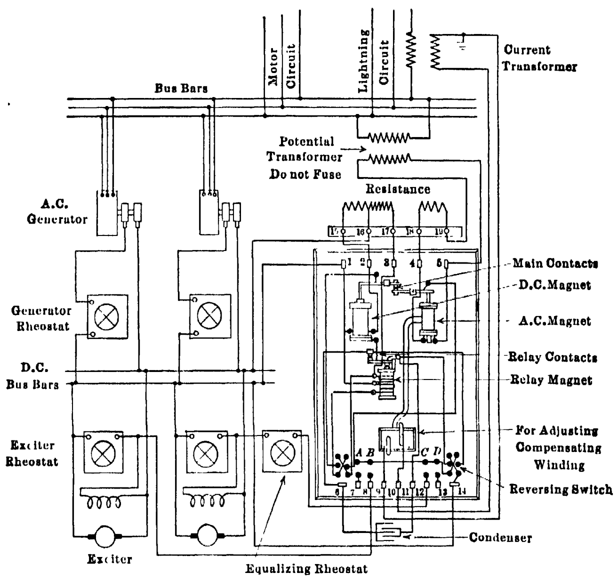

FIG. 44.—Tirrell regulator connections for two exciters in parallel.

The fundamental relation of the working parts are shown in Fig. 43. Similarly, a wiring diagram is shown for the parallel operation of exciters and generators in Fig. 44.

The Multi-Recorder.—The design and magnitude of generating stations have reached the stage where it is essential to have an accurate record of all happenings in the station. The multi-recorder has been developed to record, within fractional seconds, all important events such as opening and closing of switches, starting and stopping of generators, surges, lightning disturbances and the like. Such a device affords a valuable check on the operating staff, but more important still is the record in emer-

gencies when a number of things happen almost simultaneously and the attention of the operators is distracted from accurate observation by the necessity of action. Hence, any record of disturbances could be made afterward, only from memory, which is not very accurate in any period of excitement. It is just in such abnormal conditions that the most complete and accurate record is of greatest importance to enable the engineers to determine, with certainty, what happened and why it happened, so as to take steps to guard against its recurrence.

A brief analysis of any assumed breakdown in a power system shows that there are always two, or more, theoretical explanations from which deductions must be made for correcting the possibility of repetition. If the conclusion is that the line transformer insulation failed the correction is made for it, always with the hope that the trouble will be obviated in the future. The multi-recorder eliminates the conjecture, and from a study of sequences, before and after the trouble, a definite conclusion may be reached as to the causes.

This instrument prints a record on a strip of paper which is moved forward only when some operation takes place. So rapid is the paper-moving mechanism that it is possible to record four separate events in 1 sec. Those occurring less than ¼ sec. apart are recorded as simultaneous.

The multi-recorder, in itself, can not operate unless the necessary contacts and auxiliary apparatus are used to energize it. The contacts are placed on various switches or other movable parts of the apparatus of which records are to be made, and these contacts are wired to small electromagnets on the multi-recorder, each magnet controlling a type wheel which bears both a number corresponding to the switch and a dash (—). The type wheels are arranged on a spindle together with similar wheels which at the time of printing give the day of the week, the hour, minute and second. All of these type wheels are struck at once by printing hammers whenever an operation takes place, and the record is thus stamped on the paper in much the same way as a typewriter prints. If a switch is closed, the number allotted to this switch appears on the record. If it is open, a dash appears instead of a number. The printing mechanism of this instrument operates only when some phenomenon is occurring in the station which actuates the printing mechanism. The paper is then stepped forward.

At the present time, the multi-recorder is designed for operation by current from a 24-volt storage battery. Three amperes at 24 volts are required, momentarily, for each operation and the wires to the auxiliary switches should be of such size as to have a resistance not exceeding 2 ohms. The apparatus is made for either 20 or 50 points, which will record 20 or 50 separate and distinct operations in the power house such as closing of oil switches, lightning surges or other phenomena.

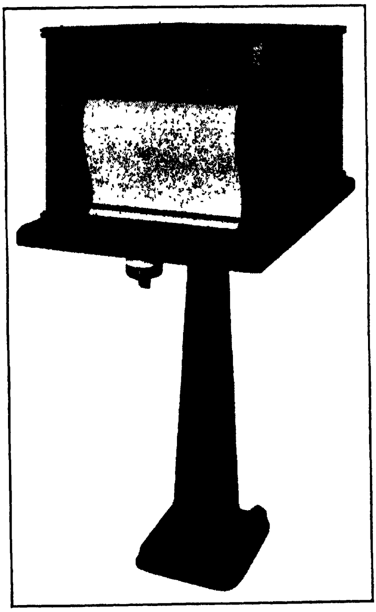

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FIG. 45.—Multi-recorder.

In order to have the multi-recorder make records of surges of high frequency which arise in the line, it is necessary to install a coherer surge indicator, which is connected in the lead from the lightning arresters to ground. This device operates on the well-known principle of the coherer and by means of relays, can be made to actuate a contact connected to the multi-recorder, thus registering the passage of current through the lightning arrester to ground.

In order to have the multi-recorder register high or low voltage, potential indicating relays fulfill the desired purpose. These may be either three-phase, or single-phase relays, and are so constructed that while normal voltage is on the line a contact is made which closes the circuit.

Fig. 45 shows a 50-point multi-recorder and Fig. 46 is a portion of a record made on one of these instruments, only 12 points on the record being shown.

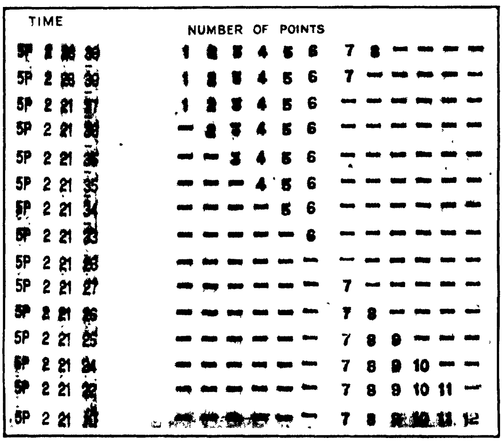


FIG. 46.—Portion of record sheet of multi-recorder.

General Methods of Switching.—There are no set rules governing the wire connections of a station and the best means must be taken to protect the system against possible service interruptions.

Improved methods are being introduced which minimize the troubles resulting directly from abnormal line voltages, but as long as switching is done in the high-tension side, high-frequency surges will occur, which tend to injure the station apparatus.

Connections from generators to lines should be so arranged that a line with generating capacity enough to charge it, can be isolated from the rest of the system for testing purposes. This is accomplished by means of the "ring" bus shown in Fig. 47, with the required disconnnecting switches.

By this arrangement the high-tension transformers are paral-

leled on the low-tension side. The bus is sectionalized by oil switches.

Note that in this diagram, oil switches are represented by small rectangles, generators by circles, reactances by coils, and transformers by the pairs of serrated lines, which signs will be used to represent these subjects in succeeding figures.

Except in very large stations, the use of a double bus is unwarranted as sufficient flexibility can be obtained by use of the ring bus in addition to the advantage mentioned.

The current-limiting reactances X, shown in the diagram, become advisable only when the generating capacity exceeds 40,000 kw. They are for limiting excessive flow of current under short-circuit conditions.

Considering now the high-tension lines, it is assumed that there will always be at least two circuits in parallel from generators to

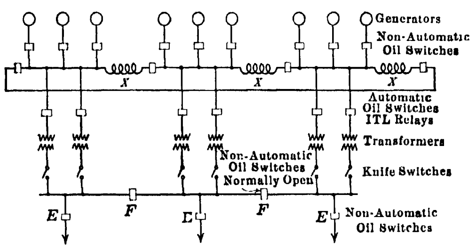


FIG. 47.—Sectionalized "ring bus" for paralleling high-tension transformers on the low tension side.

load, a condition which should exist if stress is laid on continuity of service. In order to avoid communicating trouble from one circuit to another, they should not be tied together on the high-tension side of the transformers. Where so united, any line disturbance, be it a high-voltage or a high-frequency surge, is impressed directly on all lines, limited only by the damping effect of the line itself, and further aggravated by the fact that the whole system, acting as a condenser, discharges itself through any breakdown in insulation. On the other hand, if lines are paralleled on the low-tension side only, the interposition of the transformers adds materially to the damping effect and the disturbance is limited to the damaged line.

Further, if transformers are paralleled on the high-tension side, their equivalent reactance in series with a fault in a given line

is only one-nth the reactance which would be effective were one bank only in series with the line, n being the number of banks in parallel.

If a transformer bank is made equivalent to the kilowatt capacity of one transmission circuit, and paralleled only on the low-tension side, as shown in Fig. 48, each bank can be regarded as part of the line and all ordinary line switching can be done on the low-tension side.

The disastrous effects of high-tension switching in adjacent high-voltage circuits, have been demonstrated on several transmission systems. Transient voltages from switching rise to

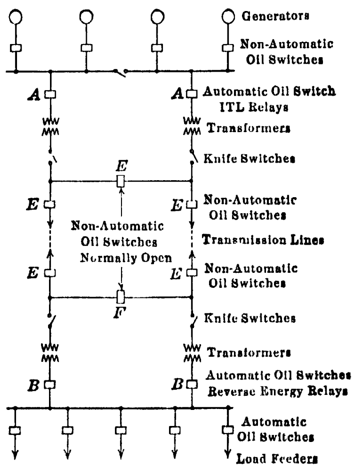


FIG. 48.—Arrangement for paralleling high tension transformers on the low tension side.

many times the normal value and may materially affect the life of the station apparatus. They become apparent in transformers with primary windings designed for 50,000 volts and over, since in such designs the electrostatic capacity of the transformers becomes considerable. These transient voltages are not produced when switching is done on the low-tension side. Many apparatus troubles, especially in transformers, are simply the culmination of a long series of slight injuries from high-voltage switching which have gradually weakened the insulation until some comparatively slight abnormal condition causes the final breakdown.

There is a number of incidental advantages from this scheme of treating the transformers as part of the line rather than part of the generators. As a rule, the number of high-tension circuits will be less, and the corresponding number of oil switches reduced, effecting a saving in the station cost and in floor space.

If line troubles automatically open the low-tension switches, the defective feeder may be segregated, and under emergencies, any line may be operated from any bank of transformers. The system should of course be operated with the switches at F open.

If an arrangement involving three banks of transformers feeding two outgoing lines can not be avoided, connections as shown in Fig. 49 should be used.

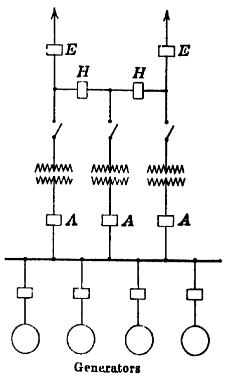


FIG. 49.—Connections for three banks of transformers feeding two transmission lines. Transformers paralleled on low tension and high tension sides.

Switches at E should be non-automatic but those at A and H should be automatic, instantaneous relays being used at H and inverse time-limit relays at A. Substation connections should be the same as shown in the figure, except that switches corresponding to A should have reverse-energy relays. With this arrangement, a short-circuit on a line would cause switches at H, in the power plant and the substations, to open first, and since no transformer is de-energized and no load circuit actually interrupted, the disturbance will be comparatively small. Switch A, in the short-circuited line, will then open at the substation by reversal, and at the main station, by overload. With a short-circuit in any transformer, selective operations will be obtained since the switches at H will open first.

Paralleling all lines to a substation bus involves taking all of the load feeders from the same common bus. Systems have sometimes been laid out on the assumption that the load requiring particularly good service should have separate supply from the main stations. Present tendencies are against such practice. A change of load, or other disturbance, will cause less change in supply voltage if power is drawn from a common substation bus than if the supply circuit is segregated back to the power house,

and a bus fed from a number of lines is not likely to lose its power supply.

Summarizing, all cases should be treated individually; in *general, circuits and generators should be run in multiple and the transformer banks should be considered as part of the line* and not as part of the generators. This latter scheme becomes a means of eliminating high-tension switching and its attendant menaces to the life of the station apparatus.

Locations of Control Boards, Buses, and Switches.—In water-power stations of very large capacity, it is preferable to have the control board on a gallery or mezzanine floor above the level of

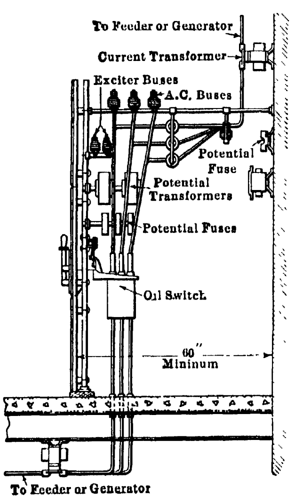


FIG. 50.—2300-volt switchboard.

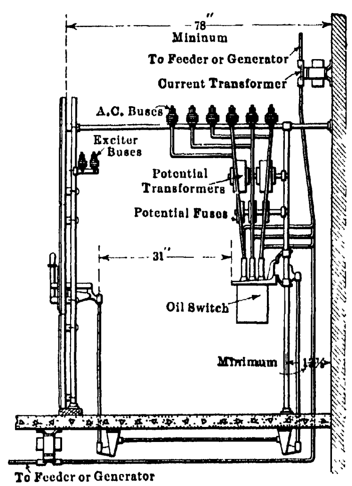


FIG. 51.—6600-volt switchboard with double busbars.

the generators. This affords the operator an uninterrupted view of what takes place on the main floor and insures his being familiar with all sequences of starting up and synchronizing. This arrangement is also advisable if there is any possibility of the main floor becoming flooded. This position of the control board is desirable for either a hand or electrically controlled equipment, the former of which may be operated by means of bell cranks and hangers allowing the oil switches to be mounted at any reasonable distance from the control panels.

The location of oil switches and accessories in the main circuits

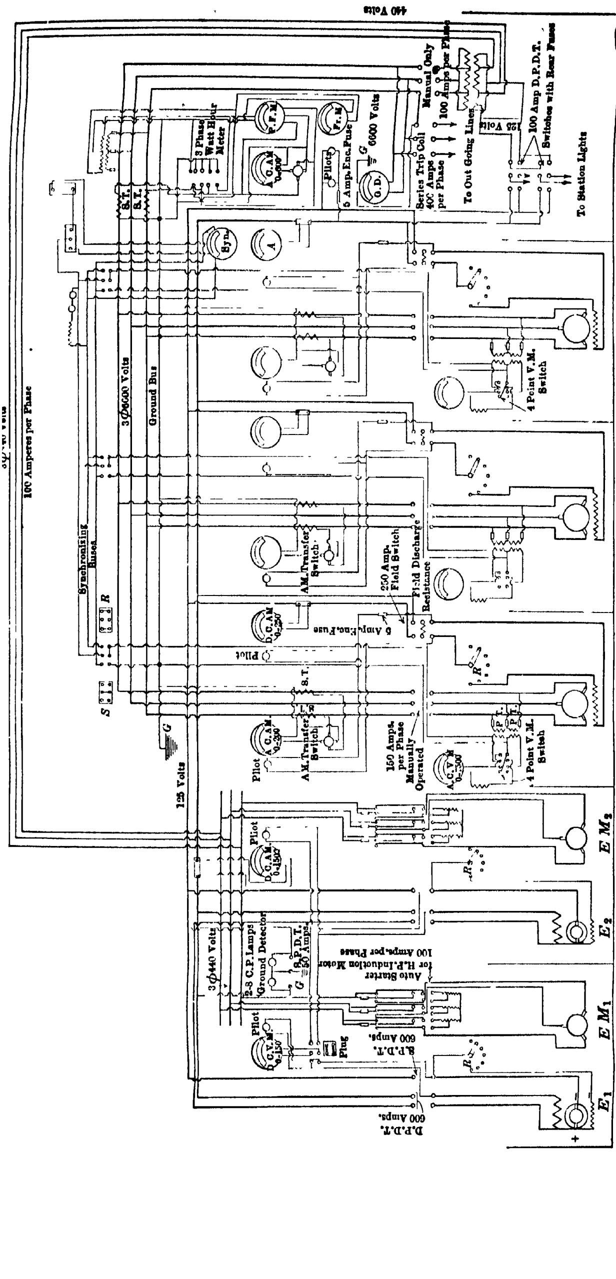


FIG. 52.—Switchboard wiring diagram for three generators and 2 motor-driven exciters.

is best determined by machine positions with a view of minimizing the length of the connecting cables.

Figure 50 shows an excellent arrangement for a 2300-volt manually controlled switchboard. Fig. 51 shows a good arrangement for a 6600-volt manually operated board with two sets of busbars.

The diagram shown in Fig. 52 is that of a 6600-volt manually controlled switchboard. The exciters are motor driven, and the

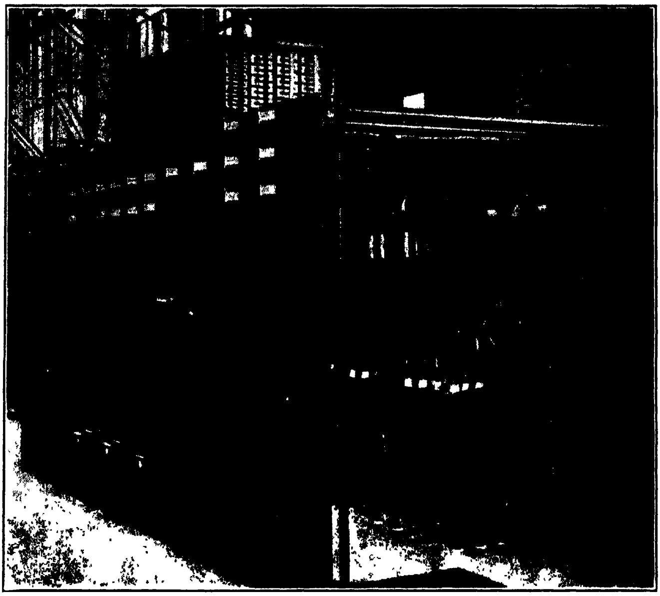


FIG. 53.—Switchboard, manually operated oil switches. (Rheostats at top of board.)

handles of the motor starters are mounted on the exciter panels. The 440-volt circuit is for the exciter motors and other station power supply.

It is to be noted that the station lighting supply may be taken from either the exciter circuit or from a low-voltage tap on the station transformers depending on the direction in which double-throw lighting switches are thrown.

Figure 53 is a photograph of a small, manually controlled

switch board, showing edgewise instruments, rheostats mounted above the board, and oil switches in the rear of the board.

Remote-control Systems.—The generator buses and low-tension feeder switches may be arranged as shown in Fig. 54.

For water-power plants, the busbars are sometimes mounted in cell compartments to avoid the possibility of fire risk and spreading of trouble from a defective part. The cell structure is built with 4-in. concrete vertical walls and 2-in. horizontal slates for the support of the insulators carrying the busbars.

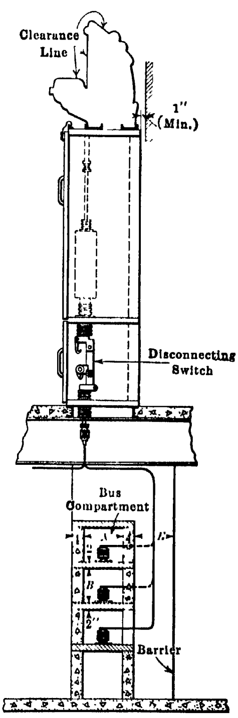


FIG. 54.—Arrangement of busbars below oil switches.

The arrangement shown in Fig. 54 can be mounted on the same gallery with the control board as the through dimension is comparatively small, but, in general, it is found advisable to mount the bus compartments on the floor with the generators, using bottom-connected oil switches on the floor above, that is, on a level with the control board. Alternative arrangements and relative positions of generator and high-tension switches and buses are shown in Figs. 55, 56, 57 and 58. The last figure shows a good arrangement for a double-busbar system.

Where space permits, it is better to house all parts within the station which may require attention or repair. It is desirable to mount the high-tension apparatus and switches outdoors when conditions permit. This obviates the necessity of separate compartments for the high-tension switches and buses. There are two variations of this arrangement, one being that in which all apparatus beyond the transformers is mounted outside the station; the other, that in which the transformers are placed outdoors together with the high-tension switch gear and accessories. The relative advantages of the indoor and outdoor installations seem to be in favor of the former, where the size and location of the generators demands a building of such di-

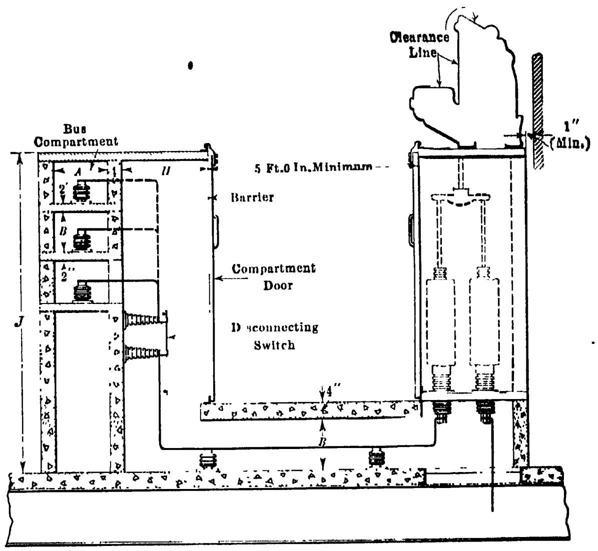


FIG. 55.—Arrangement of oil switches at distance from busbars.

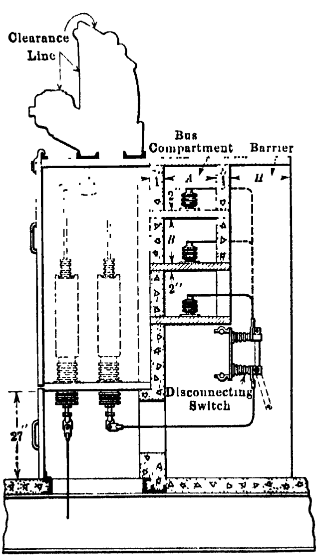


FIG. 56.—Arrangement of busbars and oil switches at same level.

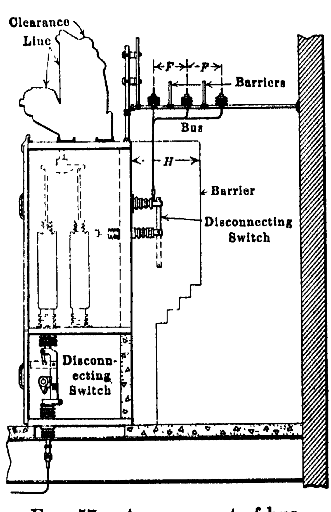


FIG. 57.—Arrangement of busbars and oil switch.

mensions that the auxiliary equipment may be housed in it, without appreciable increase in its size. On the other hand, when units of small capacity are used and are few in number, a balance of first cost is in favor of locating transformers and high-tension switching apparatus outdoors. This subject is more fully discussed in Chap. V.

Benchboards.—Switching arrangements are frequently provided in which the switches and rheostats are electrically controlled, and operated by small manual switches, or push buttons. These control switches are mounted on a long marble-topped, or slate-topped, bench, or desk. Miniature busbars are laid out on the surface of the desk, which carry no current but form a facsimile of the actual busbar connections. In this miniature scheme, the control switch for any main switch is placed in the same position with respect to the small busbars as is the main switch with respect to the actual busbars, so that the operator can see what connections are being made, at any time. The indicating and recording instruments are usually mounted on vertical panels located above the bench. Fig. 59 shows the arrangement of a benchboard in which the instrument panels are mounted above the bench and supported on columns so that the operator can have a clear view of the power station, looking over the bench and under the panel. The cost of complete switching arrangements with benchboard is considerable and the expense is usually not warranted in stations having an output of under 15,000 k.w.

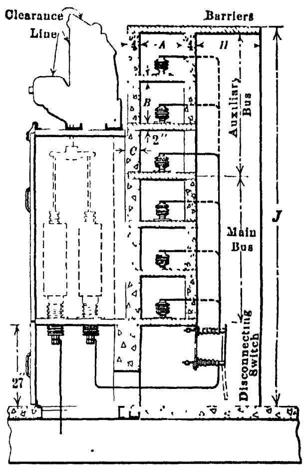


FIG. 58.—Arrangement of oil switches and busbars. Main and auxiliary busbars.

Specifications.—Following are two sets of specifications for switchboards, one for a small board for a 6000-k.w. 2300/44,000-volt station, the other for a 48,000-k.w. 6600/110,000-volt station. The former is a hand-controlled board, the latter a bench-controlled equipment. These specifications are instruc-

tive as to the requirements that the instruments, switches, and other devices must fulfill, and the various items necessary to make up a complete equipment.

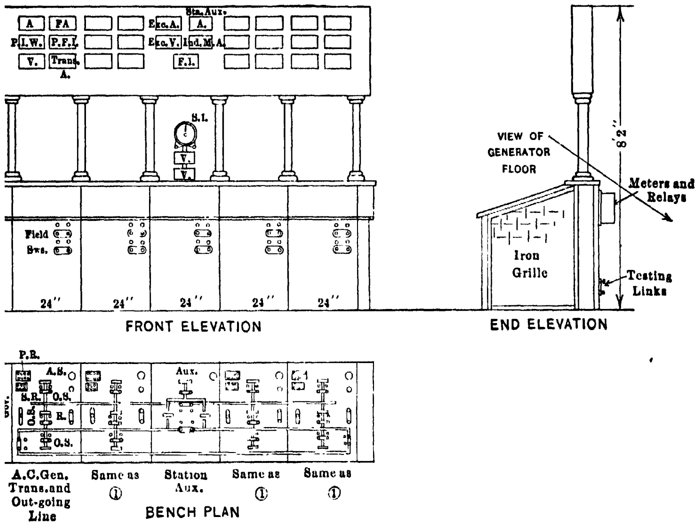


FIG. 59.—Bench control board.

SPECIFICATION NO. 1

For 5000 k.w. 2300/44,000-Volt Switchboard

1. These specifications submitted by ——————, hereinafter called the purchaser, to the contractor or manufacturer who proposes to do the work, are intended to cover the manufacture, delivery and installation of a complete switchboard. Any item necessary for the successful operation of the switchboard covered in the specifications and not shown on the accompanying blue prints, or *vice versa*, shall be furnished as if called for in both instances. The purchaser reserves the right to reject any or all details of the equipment which may prove defective in the course of one year from acceptance test.

2. The contractor shall prepare drawings showing the front and back of the switchboard and arrangement of the switching apparatus and submit them to purchaser for approval before proceeding with work in the factory.

3. The contractor shall furnish and install in conduit, in an approved manner, all instrument and control wiring between the switchboard and parts of the same remote therefrom.

4. The contractor shall hold the purchaser free from suit or lawful

damages in case of patent infringement on material furnished under these specifications, and shall furnish counsel and pay indemnity for delays caused by injunctions granted.

5. The engineer in charge shall have the privilege of inspection during the manufacture of the switchboard in the factory and any part may be rejected if, in his opinion, it does not fulfill the requirements of these specifications.

6. The contractor shall submit a detailed bill of material covering apparatus which it is proposed to furnish and mention these specifications and any exceptions which are being taken. These exceptions must first have the approval of the engineer in charge, or his duly appointed representative.

7. The material of panels shall be natural, black-oiled finish, Monson slate free from metallic veins or other defects, and of good insulating qualities. The panels shall be 90 in. high, each composed of two sections. They shall be of such thickness as to render them mechanically strong enough to support all apparatus and withstand all strains due to closing or opening of devices mounted thereon without danger of breaking. No panel shall be less than 2 in. thick. They shall be of sufficient width to accommodate the apparatus mounted thereon, allowing proper space between devices. The panels shall have a $\frac{3}{8}$-in. bevel on all front edges. The supporting framework shall consist of substantial iron pipe and fittings finished in a suitable manner. The pipe for the tie-rods to the wall will be furnished by the purchaser but the fittings for them must be supplied by the switchboard builder.

8. Each oil switch specified hereinafter shall be subjected to an insulation test, at least equal to that prescribed in the standardization rules of the American Institute of Electrical Engineers. Insulators shall be of one piece, high-grade, wet-process porcelain of sufficient length to extend through the cover plate to the contacts below the surface of the oil. Insulators must be securely held in place by metal clamps. Contacts must be so constructed that a clean surface is maintained by a wiping motion thereon. Liberal working contact area must be provided which will be amply protected from pitting by substantial renewable burning tips. Double break shall be provided for each pole. Each part is to be accurately constructed in order to insure perfect adaptability to any like oil switch or to any similar function in the same switch. A sufficient quantity of high-grade mineral oil having high flash and ignition points, is to be furnished with each switch. Hand-operated automatic switches shall trip free from the operating handle and the mechanism shall include a device for indicating from the front of the board whether the switch is open or closed. Switches must be closed through a toggle so constructed that the greatest pressure on the contacts is obtained at the completion of the stroke. Switches must be held in open position by gravity. No

part of a switch shall have a temperature rise greater than 30°C. above the surrounding air when carrying full-rated current. The switches shall be capable of opening a short-circuit supplied by the combined capacity of the generators hereinafter mentioned, without injury to themselves.

9. Switchboard will control:

Three 2000 kw., 80 per cent. power factor, 2300-volt, three-phase, 60-cycle, waterwheel-driven generators, 25 per cent. overload for 2 hr. Each generator with 40-kw., 125-volt, direct-connected exciter.

One 40-kw., 125-volt, auxiliary exciter, direct-connected to 2300-volt, three-phase, 60-cycle, squirrel-cage induction motor.

Six 666-kv.a., 2300/44,000-volt, single-phase transformers connected in two three-phase banks.

Two 2000-kv.a., 44,000-volt, three-phase outgoing lines.

Three 10-kv.a., 2300/220-110-volt, single-phase, transformers, delta-connected for station auxiliaries and lighting.

Switchboard will consist of

One swinging bracket.
Four exciter panels.
One station auxiliary panel.
One regulator, bus tie and exciter motor panel.
Three generator panels.
Two low-tension transformer panels.
High-tension disconnecting switches and oil switch.
Lightning arresters.
Choke coils.

Item No. 1.—One swinging bracket having mounted thereon:

One 110-volt, 60-cycle, synchronizing indicator with lamps.

One 150-volt, exciter voltmeter, synchronizing plugs and potential plug.

Item No. 2.—Four direct-current exciter panels, capacity 125 volt, 40 kw. Equipment per panel:

One 500-amp. ammeter with shunt.
One handwheel and mounting for field rheostat.
One four-point potential receptacle.
One T.P.S.T., 250-volt, 400-amp. main switch.
One handwheel and mounting for equalizer rheostat, copper for interconnections between the above apparatus and to the buses.

Item No. 3.—One station auxiliary panel, capacity 2300/220-110 volt, 30 kw. Equipment:

One D.P. inverse time-limit, overload relay

One T.P.D.T., 2500-volt, automatic oil switch on pipe framework remote from panel, including pipe framework and fittings for supporting the switch and interconnections between the switch, current transformers and buses.

Two 10-amp. current transformers.

Four T.P.S.T., 250-volt, 100-amp. fused, lever switches. Also copper for interconnections between the above switches.

Item No. 4.—One regulator, bus-tie exciter motor panel, capacity 2300 volt, 75 hp. Equipment as follows:

One automatic, generator voltage regulator and accessories.

One D.P.D.T. fused, knife switch for connecting regulator to either bus.

One T.P.D.T., 2500-volt automatic overload, hand-operated oil switch on pipe framework, remote from panel, including pipe framework and fittings for supporting the switch, connections between the switch, disconnecting switches, current transformers and buses.

One T.P.S.T., 2500-volt, 800-amp. non-automatic, hand-operated, bus-tie oil switch on pipe framework, remote from panel, including pipe framework and fittings for supporting the switch and connections between the switch, disconnecting switches and buses.

One D.P. inverse time-limit, overload relay.

Two 30-amp. current transformers.

Six S.P.S.T., 2500-volt 300-amp. disconnecting switches on marble bases.

Six S.P.S.T., 2500-volt 800-amp. disconnecting switches on marble bases.

Item No. 5.—Three three-phase, 60-cycle generator panels, capacity 2300-volts, 2000 kw., 80 per cent. power factor. Equipment per panel:

One 5-amp. ammeter with 1000 amp. scale.

One 175-volt voltmeter.

One 5-amp. 110-volt, polyphase, indicating wattmeter with 4000-kw. scale.

One 500-amp. field ammeter with shunt.

One 110-volt, 60-cycle frequency indicator with 55–60–65-cycle scale.

One three-way ammeter switch.

One eight-point potential receptacle with four-point plug.

One synchronizing receptacle.

One chain operating mechanism for field rheostat.

One D.P.S.T., 250-volt, 400-amp. field switch with discharging resistance clip.

One T.P.D.T., 2500-volt, 800-amp. non-automatic, hand-operated oil switch on pipe framework, remote from panel, including pipe framework and fittings for supporting the switch and connections between the switch, disconnecting switches, current transformers and busbars.

One 110-volt, 5-amp. polyphase watt-hour meter.

Two 1000-amp. current transformers.

Two 2200/110-volt, 60-cycle potential transformers with protective fuses.

Six S.P.S.T., 2500-volt, 800-amp. disconnecting switches on marble bases.

Item No. 6.—Two low-tension transformer panels, capacity 2300 volts, 2,000 kv.a. Equipment, per panel, as follows:

One 5-amp. ammeter with 1000-amp. scale.

One D. P. inverse time-limit, overload relay.

One three-way ammeter switch.

One T.P.D.T., 2500-volt, 800-amp. automatic overload hand-operated oil switch on pipe framework, remote from panel including pipe framework and fittings for supporting switch and connections between the switch, disconnecting switches, current transformers and buses.

One 110-volt, 5-amp. polyphase, watt-hour meter.

Two 1000-amp. current transformers.

Two 2200/110-volt, 60-cycle potential transformers.

Six S.P.S.T., 2500-volt, 800-amp. disconnecting switches on marble bases.

Item No. 7.—Two high-tension transformer and outgoing line equipments, each consisting of:

Six S.P.S.T., 44,000-volt disconnecting switches on separate steel bases (indoor type).

Three 40-amp. series ammeters mounted on 44,000-volt post-type insulators.

Three 44,000-volt choke coils on separate steel bases (indoor type).

One 44,000-volt aluminum-cell, electrolytic lightning arresters (indoor type) complete with tanks, horn gaps, electrolyte, supporting framework and accessories.

Item No. 8.—One high-tension transfer equipment consisting of:

Six S.P.S.T., 44,000-volt, front-connected disconnecting switches on separate steel bases.

One T.P.S.T., 44,000-volt, non-automatic, hand-operated (indoor type) oil switch.

Item No. 9.—Bus material for exciter and 2300-volt buses including necessary supporting insulators.

Item No. 10.—Back of board type current and potential calibrating terminals for all 2300-volt circuits equipped with instrument transformers.

SPECIFICATION NO. 2

For 48,000 kv.a., 6600–110,000-volt Switchboard

(General paragraphs, 1 to 6 inclusive, identical with similarly numbered paragraphs in Specification No. 1.)

7. The material of panels shall be natural black, oil finish, Monson slate free from metallic streaks, or veins, or other defects and of good insulating qualities. The slate slabs shall be of such thickness as to render them mechanically strong enough to support all apparatus and withstand all strains due to closing or opening of devices mounted thereon without danger of breakage. No panel shall be less than 2 in. thick. The panel shall be of sufficient width to accommodate the apparatus mounted thereon allowing proper spacing between devices. Panels shall have a ⅜-in. bevel on all front edges. The supporting framework shall consist of substantial iron pipe and fittings finished in a suitable manner. The pipe for the tie-rods to the wall, where necessary, will be furnished by the contractor, but the fittings for them must be supplied by the manufacturer.

The switchboard is to be of the gallery type, bench-control board, illustrated in accompanying blue prints. The proposed dimensions of slate slabs, instruments and meter locations, and arrangement of control devices are to have the sanction and approval of the engineer in charge. There shall be provided on the face of the benchboard, mimic busbars so arranged in connection with the control devices that a graphic indication is shown the operator of the existing positions of the oil switches with respect to the busbars.

Oil Switches—6600-volt Switches.—Each pole of the oil switches specified hereinafter, shall consist of a separate unit in which the circuit is broken under oil within a seamless steel vessel. Switches are to be arranged for mounting in brick or concrete cells, the necessary slate, soapstone, doors, structural-steel work and fittings for the cell to be included. Each oil switch hereinafter specified shall be subjected to an insulation test at least equal to that prescribed in the standardization rules of the American Institute of Electrical Engineers. Switches and contacts must be so constructed that a clean surface is maintained by a wiping motion thereon. Liberal working contact area must be provided which will be amply protected from pitting by substantial burning contacts. Double break shall be provided for each pole. Each part is to be accurately constructed in order to assure adaptability to any like oil switch or to any similar function in the same switch. A sufficient quantity of high-grade mineral oil of high flash

and ignition points is to be furnished with each switch. No part of any switch shall have a temperature rise greater than 30°C. above the surrounding air when carrying full rated current. Switches shall be operated by means of a motor-driven mechanism capable of positive operation on from 70 to 140 volt, direct current, without injury to the switch or mechanism. The mechanism is to be positive in its operation and equipped with the necessary auxiliary devices to insure the completion of, and to prevent any action beyond, the desired stroke, excepting in the case of an automatic switch which shall trip free of the control mechanism, which switch mechanism shall be so designed that the motor current is not carried through the control switch. A sufficient air space is to be provided above the surface of the oil to permit of a gradual discharge of any gases which may be generated in the operation of the switch under load. The ultimate total power, including overloads of 1 hr. or more, feeding the buses of the generating station will be 48,000 kv.a. maximum. Each oil switch furnished under these specifications for this station shall be suitable for this capacity under all probable conditions of service.

Control switches shall be so constructed that they return to the open position by means of a spring, and so designed that their operation will be comparatively slow, thus avoiding accidental action. They shall be provided with a mechanical device to indicate which throw was last closed, and in addition, red and green indicating lamps to indicate the actual position of the oil switch, are to be furnished. The necessary auxiliary switches for the operation of these lamps shall be provided with the oil switches.

110,000-volt Switches.—Each pole of the switches hereinafter specified shall consist of a separate, top-connected unit mounted in a steel bank. Switches are to be of a design which will avoid the necessity of any barriers or cells. Each oil switch specified shall be subjected to an insulation test at least equal to that prescribed in the standardization rules of the American Institute of Electrical Engineers. Bushings shall be of sufficient length to extend through the cover to the contacts below the surface of the oil. The exposed portion shall be constructed in such a manner that a sufficient surface is protected from rain or snow to give the required insulation with the switch entirely exposed to the weather. Bushings must be secured to the cover by metal clamps in order that they may be easily removable for inspection or repair. Contacts must be so constructed that a clean surface is maintained by a wiping motion thereon. Liberal working contact area must be provided which will be amply protected from pitting by substantial renewable burning tips. Double break shall be provided for each pole. Each part is to be accurately constructed in order to insure perfect adaptability to any like oil switch or any similar function in the same switch. A sufficient quantity of high-grade mineral

oil having high flash and ignition points and low carbonizing properties is to be furnished with each switch. Oil must be capable of withstanding a minimum temperature of $-15°C.$ without decreasing the stated rupturing capacity of the switch. All hand-operated switches shall trip free from the operating handle. Switches must be held in the open position by gravity. The operating mechanism shall be made up of parts having a dustproof finish.

Non-corrosive pins are to be used throughout and the mechanism shall be enclosed in such a manner as to give it proper protection from the weather. No part of the switch shall have a temperature rise greater than 30°C. above the surrounding air when carrying full rated current excepting that in switches equipped with bushing-type current transformers, the transformers and their enclosing casing shall have a temperature rise not to exceed 45°C.

The ultimate total power, including overloads of 1 hr. or more, feeding to buses of the generating station will be 48,000 kv.a. maximum. Each oil switch furnished under these specifications for this station shall be suitable for this capacity under all probable conditions of service. The solenoids called for in these specifications are to be capable of positive operation on from 70 to 140 volts, direct current without injury to the switch or solenoid. Each solenoid shall be provided with a control relay so connected that the current for the closing coil shall not be carried to the control switch. Solenoids shall be equipped with a waterproof hood and provision is to be made for mounting of necessary relays within this hood. The sides of the hood must be easily removable for examination. A readily accessible device for manually tripping the switch is to be included with the solenoid. Control switches shall be so constructed that they return to the open position by means of a spring, and so designed that their operation will be slow, thus avoiding accidental action. They shall be provided with a mechanical device to indicate which throw was last closed and in addition red and green indicating lamps to indicate the actual position of the oil switch are to be furnished. The necessary auxiliary switches for the operation of these lamps shall be provided with the oil switches.

9. **Switchboard will Control.**—Four 10,000-kv.a., 6,600-volt, three-phase, 60-cycle, waterwheel-driven generators, with 25 per cent. overload for 2 hr.

Four 100-kw., 250-volt, direct-current, direct-connected exciters.

One 100-kw., 250-volt motor-driven exciter with 6600-volt squirrel-cage induction motor.

One 60-kv.a., 6600/220–110-volt, three-phase, station transformer bank.

Four 10,000-kv.a., 6600/110,000-volt, three-phase, transformer banks, 25 per cent. overload for 2 hr.

Four 20,000-kv.a., 110,000-volt, three-phase, outgoing lines.

One 10-kw., 125-volt, motor-driven, auxiliary generator with 220-volt, squirrel-cage, induction motor.

One 400-amp.-hr. lead storage battery consisting of 44 cells.

NOTE.—The above 10-kw. motor-generator set and storage battery are for the operation of oil switches, indicating lamps and auxiliary devices.

10. **Switchboard Will Consist of.**—Benchboard material including slate, supporting framework, fittings, etc.

Four generator control equipments.

Three bus-tie equipments.

One station auxiliary equipment.

Four low-tension transformer equipments.

Four high-tension outgoing-line equipments.

One high-tension bus-tie equipment.

Four 110,000-volt lightning arresters.

Twelve 110,000-volt choke coils.

Two 6600-volt busbar limiting reactances, high- and low-tension bus material with supporting insulators, dash feed of multi-contactor control and instrument cable.

Item No. 1.—Benchboard material consisting of slate slabs with end pieces, supporting pipe framework, ornamental pedestals, all as indicated in the attached blue prints. Mimic bus material.

Item No. 2.—Four three-phase, 60-cycle generator equipments, capacity 6600 volt, 10,000 kv.a.

Each equipment to consist of:

One 5-amp. ammeter with 1200-amp. scale.

One —— amp. field ammeter with shunt.

One 5-amp., 110-volt polyphase indicating wattmeter with 20,000-kw. scale.

One 5-amp., 110-volt, balanced, three-phase power-factor indicator with 60–100–60 per cent. scale.

One 175-volt voltmeter.

One eight-point potential receptacle with four-point plug.

One six-point synchronizing receptacle.

One three-way ammeter switch.

One governor control switch.

One rheostat control switch.

Two field switch control switches.

One T.P.S.T., 6600-volt, 1200-amp., motor-operated oil switch for mounting in brick or concrete cell with separate compartments.

For bottom connection of main cables.

One oil switch control switch with indicating lamps.

Three T.P.S.T., 6600-volt, 1200-amp. front-connected disconnecting switches on separate steel bases.

Two 6600/110-volt, 60-cycle potential transformers with primary and secondary protective fuses.

Two 1200-amp. current transformers.

One 5-amp., 110-volt, polyphase, watt-hour meter.

Item No. 3.—Three bus-tie equipments each consisting of:

One T.P.S.T., 6600-volt, 2000-amp. motor-operated oil switch for mounting in brick or concrete cells in separate compartments.

For bottom connection of switches.

Six S.P.S.T., 6600-volt, 2000-amp. back-connected disconnecting switches on separate steel bases.

One oil switch control switch.

Item No. 4.—One station auxiliary and totalizing equipment consisting of:

One 1500-amp. exciter ammeter with shunt.

One 150-volt exciter voltmeter.

Two 5-amp. alternating-current ammeters with 10-amp. scale.

One 110-volt, 60-cycle frequency indicator with 55–60–65-cycle scale.

One pivoted bracket containing:

One 110-volt, 60-cycle synchronism indicator with lamps.

Two 175-volt, alternating-current voltmeters.

One T.P.S.T., 6600-volt, 300-amp. motor-operated oil switch for mounting in brick or concrete cells in separate compartments.

For bottom connection of main cables.

Twelve S.P.S.T., 6600-volt, 300-amp. front-connected, disconnecting switches on separate steel bases.

Four 10-amp. current transformers.

Four 6600/110-volt, 60-cycle potential transformers with protective fuses.

One oil switch control switch.

One exciter switch control switch.

Item No. 5.—Four low-tension transformer equipments capacity 6600 volts, 10,000-kv.a., each equipment to consist of:

One T.P.S.T., 6600-volt, 1200-amp. motor-operated oil switch for mounting in brick or concrete cell in separate compartments.

For bottom and side connection of main cables.

Three S.P.S.T., 6600-volt, 1200-amp. back-connected disconnecting switches on separate steel bases.

One oil switch control switch.

One 5-amp. ammeter with 1200-amp. scale.

One three-way ammeter switch.

One D.P. inverse time-limit overload relay.

Two 1200-amp. current transformers.

One 110-volt, 5-amp. polyphase, watt-hour meter.

Note.—The above watt-hour meter to be operated from potential transformers connected to the busbars.

Item No. 6.—Four high-tension outgoing-line equipments, capacity 110,000 volts, 20,000 kv.a., each equipment to consist of:

One T.P.S.T., 110,000-volt, 150-amp. solenoid-operated, outdoor-type oil switch with bushing-type current transformers and inverse time-limit overload relay mounted in the oil-switch housing.

One oil switch control switch mounted on benchboard.

Nine T.P.S.T., 110,000-volt, 150-amp. outdoor-type disconnecting switches on separate steel bases.

Three 110,000-volt, 150-amp. outdoor-type choke coils on separate steel bases.

One 110,000-volt aluminum-cell electrolytic lightning arrester, outdoor type, complete with banks, horn gaps, electrolyte, necessary supporting framework and accessories.

One high-tension bus-tie equipment consisting of:

One T.P.S.T., 110,000-volt, 150-amp. solenoid-operated outdoor-type, non-automatic oil switch.

Six S.P.S.T., 110,000-volt, 150-amp. disconnecting switches on separate steel bases.

One oil switch control switch.

Item No. 7.—High-tension and low-tension bus material including necessary supporting insulators.

Low-tension bus material to consist of:

Formed copper bar bent to shape for main buses and interconnections between oil switches, disconnecting switches, buses and reactances.

High-tension bus work to consist of:

—— feet ——— × ——— copper tubing.

Item No. 8.—Four generator field switch panels for mounting remote from benchboard, capacity 250 volt, 100 kw., size 16 by 36 by 2 on 48-in. pipe supports. Equipment per panel:

Two D.P., 250-volt, 500-amp. non-automatic, solenoid-operated, field switches with discharging resistance clips.

One auxiliary exciter switch panel, capacity 250 volts, 100 kw., size 31 by 16 by 2 on 48-in. supports. Equipment:

One D.P., 250-volt, 500-amp. automatic, solenoid-operated circuit-breaker.

One handwheel and mounting for field rheostat.

Item No. 9.—One D.C. generator and battery control panel, size 48 by 24 by 2, on 76-in. supports. Equipment:

One S.P., 250-volt, 100-amp. automatic overload release and current circuit-breaker.

One 150-amp. ammeter with shunt.

One 175-volt voltmeter.

One 80–0–200-amp. battery ammeter with shunt.

One handwheel and mounting for field rheostat.

Three four-point potential receptacles with four-point plug.

One T.P.D.T., 250-volt, 100-amp. battery switch.

One S.P.S.T., 250-volt, 100-amp. generator switch.

Two D.P.S.T., 250-volt, 100-amp. fused feeder switches.

Copper for interconnections on the back of the board.

Item No. 10.—One A.C. lighting and auxiliary panel, capacity 220–110 volts, 60 kv.a., size 48 by 32 by 1½ on 72-in. supports. Equipment:

Nine T.P.S.T., 250-volt, 100-amp. fused feeder switches.

Copper for interconnections on the back of the board.

Item No. 11.—Two power-limiting reactances.

Multi-conductor cable, each wire consisting of:

Nineteen strands of No. 22 wire in the following quantities:

——— ft. of three-conductor.

——— ft. of five-conductor.

etc.

Item No. 12.—Five supporting peaestals of approved design, each having mounted thereon:

One automatic, generator voltage regulator comp'ete with all necessary accessories for successful operation.

NOTE.—The above five regulators are to be suitable for operation with the four direct-connected exciters and the auxiliary motor-driven exciter.

CHAPTER IV

CRANES

A crane is an essential part of the equipment of any power station, provided it is erected before any of the apparatus is put in place, and used for the purpose of installing the machinery and apparatus. It will save enough to pay for itself in doing this work alone.

An overhead, travelling crane comprises a pair of rails properly supported, one being placed on either side of the power house. On each rail runs a truck called the bridge truck. Spanning the distance between the two rails and fastened to the bridge, trucks is a pair of girders called the bridge. On top of the bridge, a four-wheel carriage is placed which travels from one end to the other of the bridge, and on this carriage is mounted a hoisting apparatus. Carriage and hoist together are termed the trolley. From the hoisting apparatus is hung the lifting hook and the pulley block to which it is attached. Fig. 60 shows the outline of a hand-operated traveling crane, the bridge, trolley and crane hook being shown in elevation, while an end view is shown of the bridge trucks, at either end of the bridge. The whole crane is movable along on the runway running lengthwise of the power house, while the trolley is movable over the bridge, across the power house. These two motions, together with the hoisting, require three separate applications of power. In many instances the cranes are completely motor-actuated, there being three motors on the crane, one being provided for each of the required motions. In some cases, the movement of the bridge and of the trolley are effected by hand, a single motor being used to operate the hoisting mechanism. The most suitable crane for power-station work is one in which all of the operations are performed manually. The principal use of the crane is in erecting the machinery when it is first installed and, at that time, electric current for operating the motor is seldom available. In a large station, where a number of units are to be installed, it may, occasionally, be economical to use a motor-

driven crane and arrange for temporary current supply for it during the period of erection. This is a question which can not be reduced to a definite formula but must be fixed by the judgment of the engineer and based on the specific local conditions.

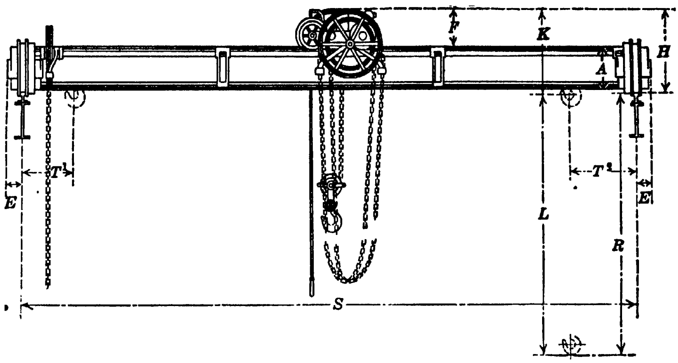


FIG. 60.—Crane-clearance diagram.

TABLE 3.—CLEARANCES FOR HAND-POWER CRANES

(Northern Engineering Works, Detroit, Michigan.)

Capacity	Span	A	E	H	F	K	T^1	T^2	Wheel base [variable]
2 and 3 tons	30′ or less	14″	5½″	2′4″	14″	3′0″	18″	16″	5′4″
2 and 3 tons	31′ to 50′	17″	7¼″	2′7″	14″	3′0″	18″	15″	5′6″
4 and 5 tons	30′ or less	17″	6″	2′7″	14″	3′8″	22″	18″	5′1″
4 and 6 tons	31′ to 50′	22″	7¼″	3′0″	14″	3′8″	22″	18″	5′3″
7 and 8 tons	30′ or less	20″	6″	3′10″	14″	3′8″	22″	18″	5′1″
7 and 8 tons	31′ to 50′	22″	7¼″	3′1″	15″	3′8″	22″	18″	5′3″
10 and 12 tons	30′ or less	20″	6″	3′2″	18″	4′1″	2′0″	20″	6′0″
10 and 12 tons	31′ to 50′	2′1″	7¼″	3′7″	18″	4′1″	2′0″	20″	6′6″
15 tons	30′ or less	22″	7¾″	3′4″	18″	5′2′	2′3″	2′3″	6′8″
15 tons	31′ to 50′	2′1½″	7¾″	3′7½″	18″	5′2″	2′3″	2′3″	6′8″
20 tons	30′ or less	22″	7¾″	3′4″	18″	5′4″	2′3″	2′3″	6′8″
20 tons	31′ to 50′	2′2″	7¾″	3′8″	18″	5′4″	2′3″	2′3″	6′8″

Hand cranes should have at least two hoisting speeds, and, preferably, three. They should be provided with quick-lowering attachments and a positive, reliable brake which will hold the load in any position. With these devices, the handling of materials and parts of comparatively light weight can be greatly expedited with a corresponding saving in time and labor. It is better to work the crane from pendant chains which hang down within reach of the power-house floor rather than from a

platform on the crane. The load-carrying cables may be either of wire rope or chain. Engineers seem to prefer chains to wire rope for the hoisting cables. The author, however, is unable to see any particular advantage of chains as compared with wire rope and has installed some thoroughly satisfactory cranes, equipped with wire-rope hoisting cables.

The factors of safety in the several parts of the crane should be not less than five or six. The following values indicate the maximum allowable stresses in the various kinds of material used in constructing cranes:

Cast iron, in compression, 15,000 lb. per square inch.

Cast iron, in tension, none, except the tension produced by flexure stresses in the frames of the bridge trucks, these not to exceed 1250 lb. per square inch.

Steel in compression, 12,000 lb. per square inch.

Steel, in tension, 12,000 lb. per square inch.

Bolts, 8000 lb. per square inch.

In computing the stresses which may act on the runways and bridge trucks, it must be remembered that the trolley carrying the maximum load may be moved out to near one end of the bridge, thereby imposing nearly all the load due to the weight of the trolley and the object lifted on one of the bridge trucks and its runway.

The total load on either bridge truck, for any position of the traveller, is:

$$R_1 = \frac{W_1}{2} + \frac{(W_2 + W_3)(l - x)}{l} \qquad (14)$$

W_1 = total weight of bridge.
W_2 = total weight of trolley.
W_3 = total weight of load.
l = span of bridge in feet.

x = distance of load chain from the nearer runway, in feet.

The total weight imposed on the runway rail is

$$R_1 + W_4$$

W_4 = weight of one bridge truck.

Obviously, the maximum load on a runway rail is when the trolley and load are moved as close to the rail as the trolley will go, that is, when the value of x is minimum.

Runways.—Runways are usually made of I-beams having a proper section to support the maximum load when this load is as near to one runway as the trolley can move it, that is, with the highest value of $R_1 + W_4$. The runway is supported at intervals by steel columns, or by brick pilasters built as interior wall buttresses. The distance apart of the supports should be from 8 to 16 ft., depending on the character of the supports, their cost, and the cost of the type of girders adopted for the runway. Where a runway is carried on top of brick or concrete pilasters, a plate of cast iron or steel is placed on top of each pilaster and held in place by anchor bolts. The steel I-beam rests on the plate and is held in position by machine bolts which pass through

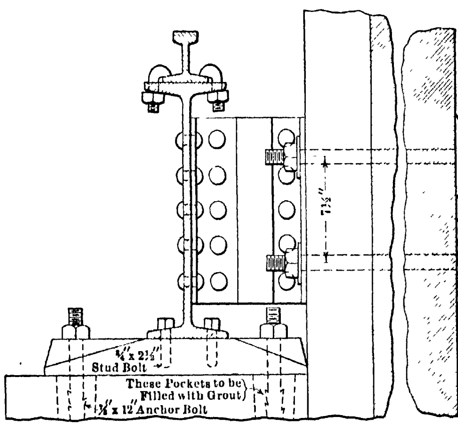


Fig. 61.—Crane runway on brick or concrete pilaster.

the lower flange of the I-beam and are tapped into the iron plate. The runway beams must also be anchored against lateral stresses. This is usually effected by fastening them to the power-station wall to which they are adjacent. The fastening is made up of a pair of short sections of angle iron joined by a gusset plate. The projecting leg of one angle is bolted to the wall with through bolts, while the projecting leg of the other angle is rivetted to the web of the I-beam. This construction is shown in Fig. 61 which is a section through one side of a runway carried on a brick pilaster. On top of the supporting I-beam is mounted a T-rail weighing 40 to 45 lb. per yard. The rail is held in place by toe-clamp bolts which pass through the upper flange of the I-beam

and clamp the rail securely in position, as shown in Fig. 61. Where runway spans between supports are of considerable length, say 16 to 20 ft., the proper depth of I-beam to carry the maximum load may be such that, although the flexure stresses are well within the limits of safety, the beam may not be strong enough to resist buckling sidewise. In this case it is customary to place a channel on top of the I-beam and bolt the two securely together so that the channel may prevent any lateral buckling of the beam. The channel may be placed with its flanges upward or downward. The rail is placed on top of the channel. In some cases the bolts which fasten the channel to the beam flange pass also through the lower flange of the rail so that all three members are bolted solidly together. Fig. 62 shows a construction of this kind.

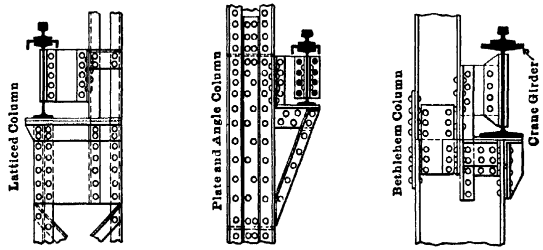


FIG. 62.—Crane runways on steel supports.

Crane runways are also made of reinforced concrete. The methods of computing the size and amount of reinforcement necessary for a given bending moment have been previously given in the discussion of "Reinforced Concrete Dams." It is to be noted that reinforced concrete beams must be strengthened to resist shear as well as flexure if the maximum shear at any support exceeds 60 lb. per square inch of total beam section.

The following are the principal formulæ for computing the bending moment and proper spacing of supports for runways:

If L = distance between supports, or lengths of span, in feet.
b = length of wheel base of bridge truck in feet.
W = total weight on runway = $R_1 + W_4$.

Maximum bending moment for one runway girder is

$$M = \frac{W}{4}\left[L - b + \frac{b^2}{4L}\right] \text{ lb.-ft.} \qquad (16)$$

or,

$$M = 3W\left[L - b + \frac{b^2}{4L}\right] \text{ lb.-in.} \qquad (16a)$$

from which the strength of the runway girder is computed.

If it is desired to use a certain size of beam for the runway, or if head-room clearances limit the height of the girder, then the distance apart of the supports may be computed from the formula:

$$L = \sqrt{\frac{2M}{W}\left(\frac{2M}{W} + b\right)} + \frac{2M}{W} + \frac{b}{2} \text{ ft.} \qquad (17)$$

M being the maximum bending moment, in *pound-feet*, allowable in the beam.

As an example, consider a crane to carry 15 tons. Weight of bridge and trucks $= W_1 + 2W_4 = 20{,}000$ lb. Therefore, $\frac{W_1}{2} + W_4 = 10{,}000$ lb.

Weight of trolley, 4000 lb. $= W_2$.

Load, 15 tons $= 30{,}000$ lb. $= W_3$.

$W_2 + W_3 = 34{,}000$ lb.

If the span of the crane is 50 ft., and the load can be carried to a point within 5 ft. of the runway rail, the proportion of $W_2 + W_3$ resting on the runway $= \left(\frac{50 - 5}{50}\right) \times 34{,}000 = 30{,}600$ lb. (See formula 14.)

Hence, maximum load on girder, or $W = 30{,}600 + 10{,}000 = 40{,}600$ lb.

Assume wheel base of bridge truck $= 6$ ft.

Assume distance apart of supports $= 16$ ft.

Then $M = \frac{40{,}600}{4}\left[16 - 6 + \frac{(6)^2}{4 \times 16}\right] = 106{,}920$ lb.-ft. $= 1{,}273{,}040$ lb.-in.

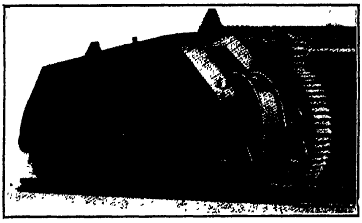
This would require a standard, 18-in. I-beam, weighing 55 lb. per foot.

Assume that the conditions of head room or stock of structural steel available makes it necessary to use a standard 15-in. I-beam weighing 55 lb. per foot. The maximum allowable bending moment, in *pound-feet*, for this beam, with a stress of 16,000 lb. per square inch, is 90,850 lb.-ft.

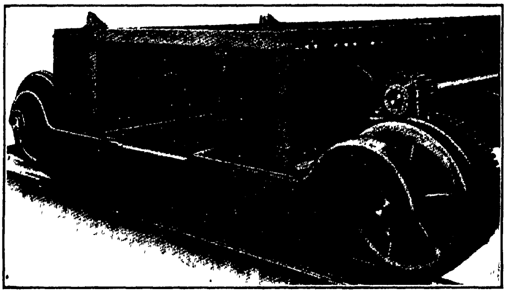
If all the other values used in the preceding example be taken, the maximum distance apart of the supports will be

$$L = \sqrt{\frac{2 \times 90,850}{40,600}(4.47 + 6)} + 4.47 + 3 = 14.33 \text{ ft. apart.}$$

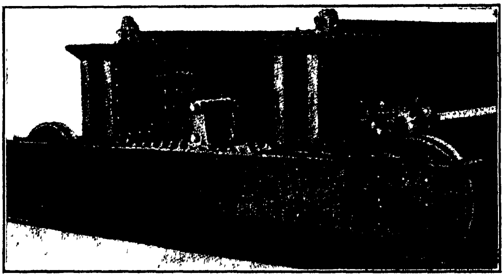
The foregoing give the theoretical values of the moments and sizes of the girders on the basis of quiescent loading. It is



a.—Cast flush type.



b.—Cast underbody type.



c.—Structural underbody type.
FIG. 63.—Bridge trucks.

customary, however, to allow 15 to 25 per cent. additional strength because of vibration and impact. Hence, the stresses

in runway supports should be taken at not over 14,000 lb. per square inch for steel girders, and for reinforced concrete should be kept within 14,000 lb. for tension in the reinforcing steel and 400 lb. per square inch compression in the concrete.

Bridge Trucks.—Bridge trucks are made in a number of designs, three being indicated in *a*, *b* and *c*, Fig. 63. The usual type of truck is that known as the "flush type," the top of the truck being flush with the top of the bridge girders. For heavier loads, the underbody type is used, the truck being formed with a depressed portion between the wheels, and the bridge girders placed on top of the truck. In both of these the truck frames are cast iron or cast steel. The truck shown in *c*, Fig. 63, is built up of structural steel and is an underbody truck, the bridge girders resting on top of the truck frame.

Clearance.—In selecting a crane it is necessary to know the clearances so that the position of the runway may be determined with reference to the sidewalls and roof truss of the building. The thickness of the bridge trucks and the total height from runway rail to the top of the trolley differ with different designs and sizes of cranes. The table given underneath Fig. 60 shows the standards of one well-known company which do not vary greatly from standards of other companies and these figures are useful for preliminary computations. These dimensions refer only to cranes having flush type of bridge trucks. The clearance from runway track to the bottom chord of the roof truss must be greater for underbody trucks.

CHAPTER V

DESIGN AND TESTING OF POWER STATIONS

It is impossible to set down any rules or formulæ for the specific design of hydro-electric power stations. With a full knowledge of the apparatus which goes to make up the equipment, and of the river conditions, the selection of sizes of machines and accessories, and the arrangement of the power plant become matters of personal judgment, influenced by the special local conditions. The only thing that can be done here is to set down, in a general way, the character of design which is sanctioned by modern practice and which, in turn, is based on the experience of the many engineers who have been engaged in this work.

Selection of Equipment.—The design of a hydro-electric plant is so intimately related to the design of the turbines and auxiliaries that the general plan is usually the joint conception of the plant designer and the turbine designer. This is particularly true of some of the more recent installations where the wheel casings, draft tubes and wheel chambers are built in concrete as integral parts of the power house. The controlling factors in the design of the power house are the turbines and generators. The power house is built around the generating units, and, hence, the general layout is determined by the design of the turbines and of the generators.

The vertical unit, although unsuitable under some conditions, has manifest advantages over other types. It combines simplicity and accessibility of mechanical parts with the superior efficiency due to an unobstructed draft tube, minimum friction of rotating parts, and convenient application of the spiral casing, which is the most efficient form of turbine casing thus far devised.

Vertical turbines have been built with two or more runners, but experience has shown that the single-runner unit is the more desirable. With multiple-runner wheels, the gate mechanism is almost entirely submerged, and can not be lubricated. The

mechanical design is more complicated, the wheels less efficient, and the entire machine is less accessible for inspection or repairs. The advantage of the multiple-runner vertical unit is higher speed, and that is not sufficient to offset its disadvantages, except under special conditions.

The best practice of today adheres to the single vertical turbine where commercially practicable. The casing is of volute or spiral form, and, for low heads, is usually moulded in the concrete foundations of the power house. For higher heads it is made of cast iron, cast steel or rivetted-steel plate, as conditions may require. Sometimes the metal casing is imbedded in concrete under the floor which supports the generator. The thrust bearing is occasionally located between the generator and the turbine and supported by the latter; but it is usually and preferably placed on top of the generator and supported by a spider mounted on the generator frame. The gate mechanism is exposed, no parts being in the water except the gates themselves, and all bearings and pin connections are accessible for lubrication. The gates are operated by two servo-motors or regulating cylinders connected in balance. No gearing, or gate shaft is required. The governor is located on the generator floor.

Horizontal turbines of the open-flume type have been built with four, six, and even eight runners per unit. These wheels, however, are open to the same objections which apply to the multiple-runner vertical unit. Too much of the vital mechanism is submerged. It can not be inspected or adjusted without shutting down the unit, and the usual result is that it is run until it breaks down or gets into such condition that it will no longer run at all.

Horizontal units may be either single- or double-discharge. Both types admit of exposed gate mechanism. The double-discharge has some advantages over the single in that it is hydraulically balanced against end thrust. On the other hand, if it is central discharge, *i.e.*, both runners discharging into a common draft tube, the draft-tube conditions are not so favorable. If, however, the runners are spaced well apart, this objection is largely overcome. One of the commonest faults in the design of central-discharge turbines, as ordinarily built, is the close spacing of the runners.

Horizontal turbines for very low heads are, necessarily, set in open flumes or wheel pits. For high heads, the volute or spiral

casing is the preferable type, the question of central, double- or single-discharge depending on the conditions to be met. For intermediate heads, the cylindrical-plate steel casing has been commonly used. It is not as efficient, hydraulically, as the spiral casing, but it is considerably cheaper. If the penstock connection is at the top or the side, the gate mechanism may be exposed, which is not the case if the penstock is connected at the end. In the latter case, however, the hydraulic conditions are better.

Whatever the kind of water-wheel case, a drain pipe and valve must be provided by means of which the case, and penstock, back to the headgates, can be completely emptied. This drain pipe must be of ample dimensions, not only to draw off the initial water, but also to take care of the continuous flow from leaky headgates. For small turbines—say up to a pair of 36-in. wheels or a 46-in. single wheel—the diameter of the drain pipe should be not less than 6 in. Larger wheels should have proportionately larger drain pipes.

The number of units in a power plant to produce a given output should be as few as can be reasonably obtained in standard apparatus. At the same time, the whole power should not be concentrated on one unit except in a special case of a water-power plant running in parallel with other power plants, either steam or hydraulic, and these other plants of such capacity that they could carry the entire load temporarily if the single unit were shut down. It must be understood that there are certain periods in the life of every machine, no matter how simple its character, when it must be out of service for inspection, repair, the renewal of parts, or some other reason, and this period of shutdown may sometimes last as long as a month or 6 weeks, this being a reasonable time within which to order a repair part, get it shipped, delivered and installed, if the part required be of any magnitude. Therefore, the capacity of any power station is equal to the maximum continuous output of all the machines operating together, less one of them. There are sporadic occasions of excessive load peak which may occur three or four times a year and for this, the total capacity of equipment may be taken as the maximum continuous output of all the machines working together, but even on these infrequent occasions, one of the units might be unavoidably shut down. For small power plants the best number of units is, usually, three. The maximum overload capacity for continuous operation is, generally, 25 per

cent. more than the normal. Therefore, if each of three units can carry 50 per cent. of the load, the three units working together will be loaded at about 80 per cent. of the normal which is around the point of best water-wheel efficiency, while if one machine is out of service, the two remaining ones can carry the entire load. As to whether three or four units should be adopted, depends on the standard machines available in the market. Generator and water-wheel sizes advance by steps with considerable difference in capacity from one size to the next, and in attempting to obtain three machines of the proper capacity it may be found that the available sizes will not permit this selection without provision of an excessive total capacity and a higher cost than by the adoption of four machines. Of course, if four machines are installed, each one should have a maximum capacity of one-third the total load. There have been numerous discussions, some even of a highly mathematical character, on the selection of the most economical generating unit. These discussions are interesting but have no practical bearing on the subject. As has been before stated, no engineer can predict what the load curve of a station will eventually be, and every hydro-electric installation is made in the hope that the demand for current will grow each year and the expectation that the equipment will have to be added to at some future time. This assumes, of course, that the maximum available power is not all capable of being converted into electric energy by the equipment at first installed. Hence, a little excess capacity, even at a small increase in cost, is not objectionable. Hair-splitting in the matter of size of equipment amounts to nothing, even if the load curve is fixed, because a few per cent. more or less in the capacity of a generating unit does not make any appreciable difference in the cost, and even if it did, exact, computed sizes of machines are not available. Generally, the cost of the generating equipment is only 10 or 12 per cent. of the total cost of the development and there is but little gained in reducing the effectiveness of a 100 per cent. investment to save 10 per cent. on 12 per cent. of it. In other words the variation of 10 to 12 per cent. in the size of the generating units will change the total cost of the development less than 1½ per cent.

Frequency.—The present practice is almost universally to adopt 60 cycles per second or 7,200 alternations per minute as the frequency for any plant, no matter what the service.

On long lines, and for low heads, 25 cycles per second has been used because of the generator characteristics, and the inductive line drop, which is proportional to the frequency, is greatly reduced and the regulation is better.

The disadvantages of this lower frequency are:

(*a*) The higher cost of transformers and motors than the costs for 60-cycle apparatus.

(*b*) The inability to operate lighting loads from 25-cycle circuit.

These so far outweigh the reduction in the inductive line drop, that 60 cycles is the value now adopted wherever the conditions of head and length of transmission permit (see Chap. I).

Shaft Connections.—Except in special instances, where the generator is built directly on top of the wheel case, and a single continuous shaft is used for both the wheel and the generator rotor, the wheel and rotor have independent shafts, and are usually built by different manufacturers. These shafts are generally connected together by flange-plate couplings, or split-tubular couplings, the coupling, in either case, being keyed to the shaft sections. Various forms of mechanical couplings have been used but the above have been found to be most reliable, satisfactory, and, in addition, cost less than other varieties.

The diameter of the shafting for turbines and generators is usually given by the formula:

$$d = \sqrt[3]{\frac{100P}{N}} \text{ in.} \tag{18}$$

d = diameter of shaft in inches.
P = maximum horsepower to be transmitted.
N = number of revolutions per minute.

The size of the shaft actually used should not be much smaller than is given by this formula.

Power House.—The power house is to be regarded as simply a protecting covering for the machine and operators, and the rational method of designing the power house is to lay out the machinery in the most advantageous manner and then plan a house to go over it.

The power station should be located as close to the dam as possible, providing that in this position, little or no tailrace excavation is required. The practice of saving a small amount of money, in reducing the length of penstocks by placing the

power house close to the dam, and then expending great sums in blasting out a tailrace, is not to be approved from the financial standpoint, when by locating the station a comparatively short

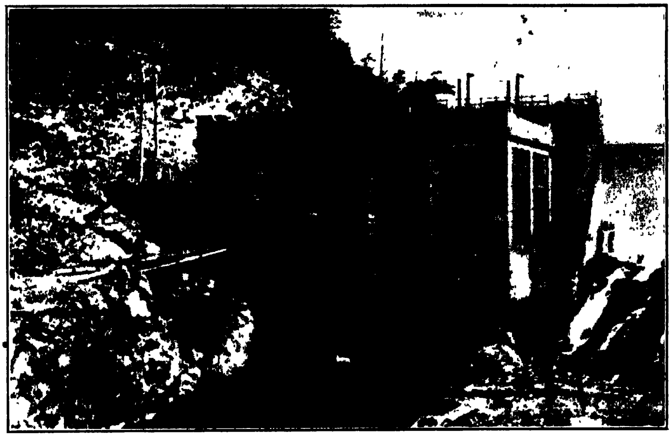


FIG. 64.—Exterior of small power station. (Discharge side.)

FIG. 65.—Exterior of small power station. (Showing bulkhead and penstocks.)

distance downstream from the dam, most of the tailrace excavation would be avoided. In any instance, the cross-section of the tailrace and the elevation of its bottom must be such that

there is no appreciable loss of head, from the draft-tube pit to the stream.

Where horizontal units are used, they are usually set on concrete or masonry arches, the supporting piers between the arches being midway between adjacent machines. The water is conducted to the turbines through pipes which enter the turbine cases at the top or at one end, as may be best adapted to the conditions, and the discharge is carried down through the crown of the arch, and discharged through the archway. The length

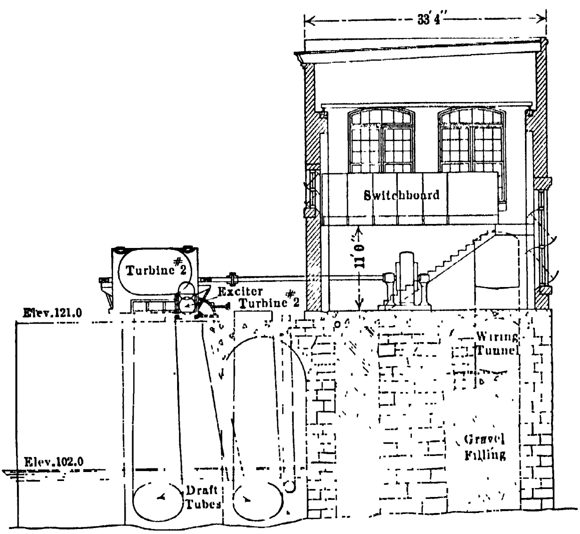


Fig. 66.—Section through small power station.

of the arch must be equal to the total length of the unit plus any additional distance represented by the width of the power house from the end of the unit to the opposite wall.

The power house itself may be built to include the entire unit, or the turbine may be left outside, the house covering only the generator, the switchboard and accessories.

The water-wheel shaft may pass through the wall of the power house, if the entire water wheel is excluded. In many instances, one end of the water-wheel case projects a few inches into the power house through the wall, the rest of the case being outside, and the wall is built up around the case so that there is no space

between the periphery of the wheel case and the circular opening through which the case projects.

These two latter methods of construction are used in latitudes south of Virginia, where there is no danger of the water in the turbines freezing when the wheels are shut down so that they may not be easily started again. Figs. 64, 65 and 66 show some

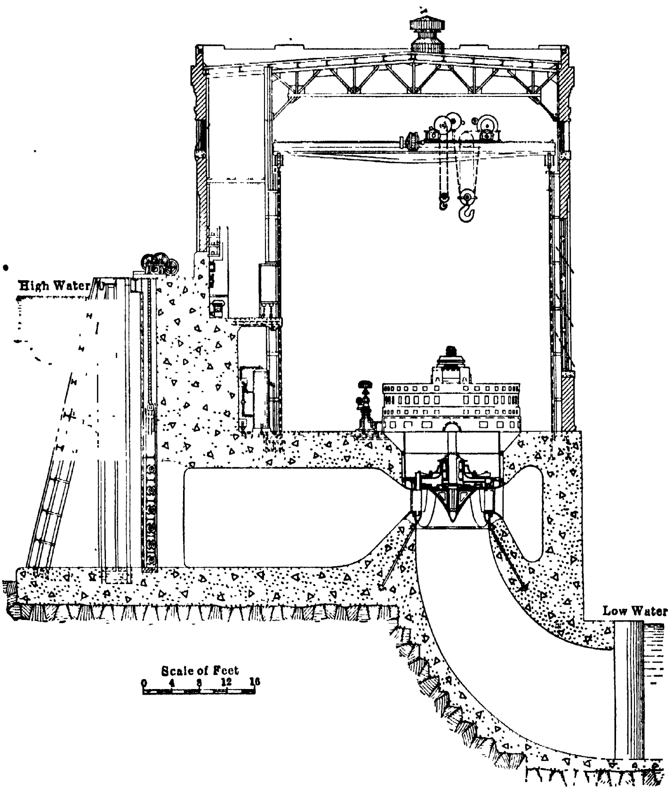
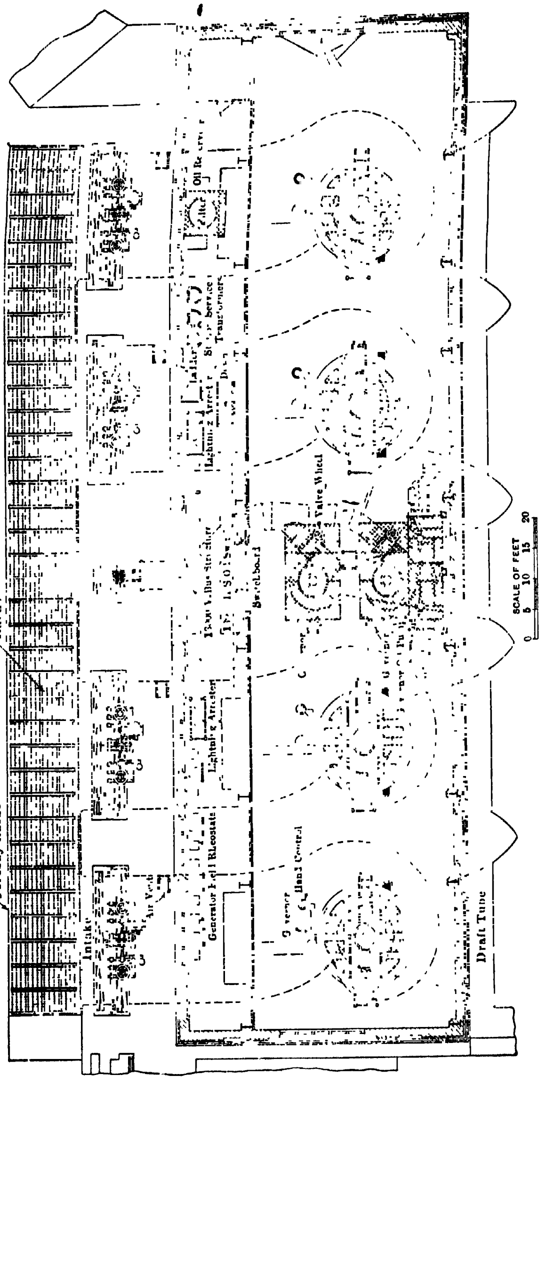


FIG. 67.—Section through power station.

small power stations of this general type. Figs. 64 and 65 show two exterior views of a small power station in Tennessee. The first of these is a downstream view and shows the arches through which the water discharges into the tailrace. Fig. 66 shows a sectional elevation of a small power plant in Georgia, in which the water-wheel platform and the discharge tunnel has



PLAN OF POWER HOUSE

FIG. 68.—Plan of power house.

at one side of the house, the wheel shaft passing from the water wheel to the generator through the wall.

Where vertical wheels are used, the cost of the foundations is greatly reduced, because the discharge arches are either comparatively short or they are formed into draft tubes so that they fulfill both the function of supporting arch and draft tube. Also, the power house required is usually smaller than that necessary for horizontal units, particularly in cold climates where the water-wheel unit must be housed to prevent freezing.

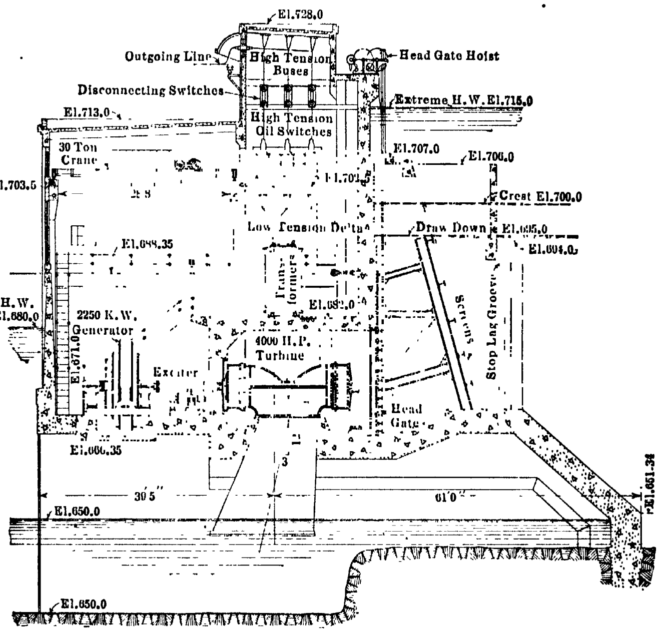


FIG. 69.—Cross-section of generating station.

Figures 67 and 68 show the general form of a power station with vertical equipment. Vertical units are not adapted for open penstock setting, except under special conditions. The general arrangement for horizontal units in open penstock settings is as shown in Fig. 69, in which the downstream wall of the wheel pit forms the upstream wall of the power house. In this case, the house must be built upon discharge arches for the passage of the water from the draft tubes.

In many installations, the bulkhead of the dam is used as the upstream wall of the power station, and where this is the appropriate location of the power house a considerable saving is effected by this double use of the bulkhead. If, however, this location of the power house necessitates excavation of a tailrace of any considerable length, such design will prove more expensive than it would if the power house were located further downstream. Fig. 70 shows the arrangement of a power house close up against the bulkhead section of a hollow reinforced-concrete dam. The

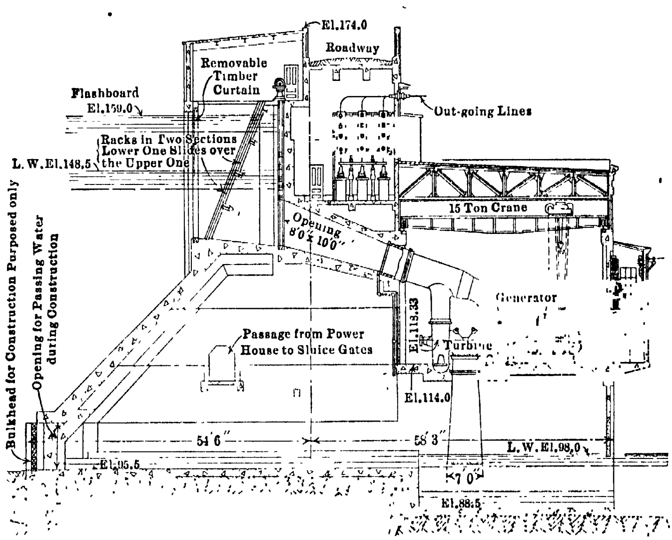


FIG. 70.—Section through power house.

location of the racks, headgate, penstock, generating unit and draft tube are all clearly shown. In this case, the turbine unit comprises two horizontal, scroll-encased wheels, each with a separate intake from the penstock, the two wheels discharging into a common draft tube.

An arrangement of vertical units, each comprising a pair of water-wheels set in a cylindrical case of reinforced concrete, fed by steel penstocks and the water discharged through steel draft tubes without any arches under the power house, is that of the Austin, Tex., plant shown in Figs. 71 and 72 one being the plan, the other the transverse section.

While there are a large number of variations in design of power

houses, they are nearly all classified under some one of the types that are herein shown.

The elevation of the water wheels is always fixed by the fact that they may not be over 22 to 25 ft. above minimum low-water

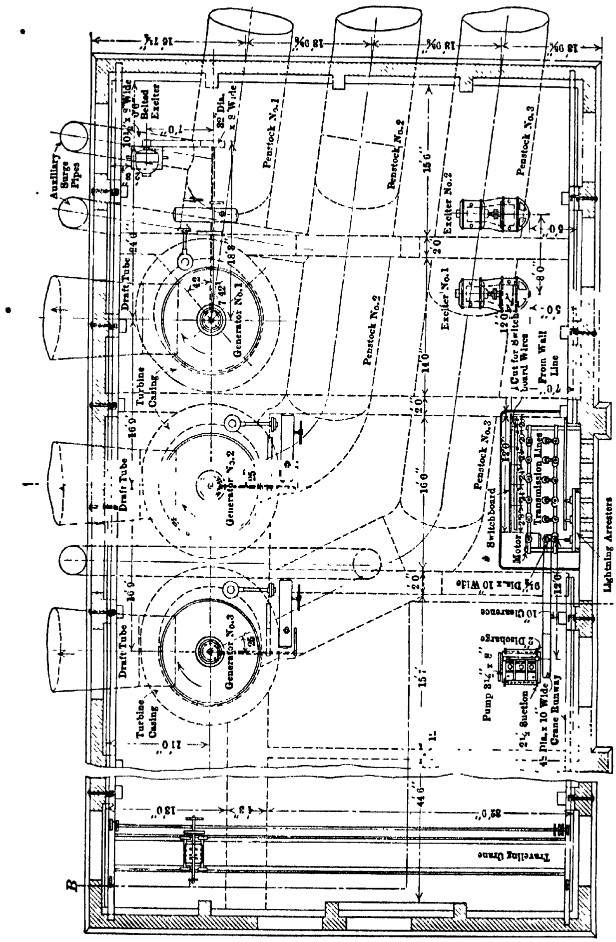


FIG. 71.—Plan of power station (Austin, Texas).

elevation and if the units are horizontal, they must be set high enough to prevent flooding the power-house floor and generators during periods of maximum high water.

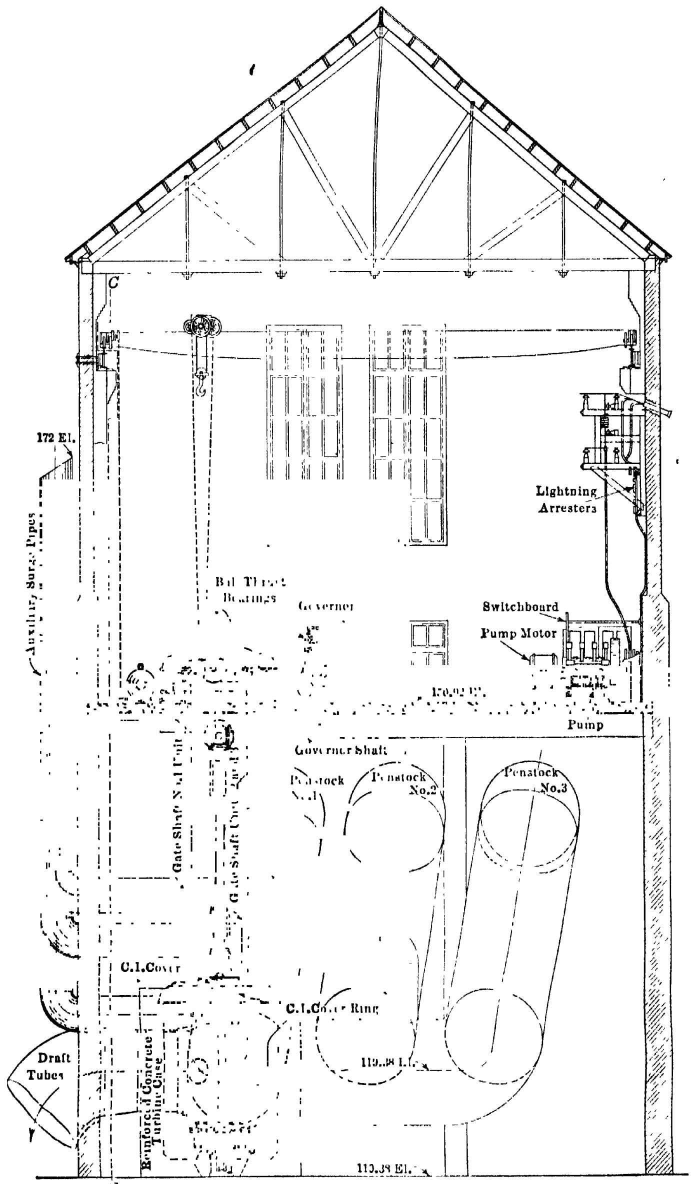


FIG. 72.—Transverse section of power station (Austin, Texas).

In the case of vertical units, the elevation of the water wheels can be fixed at any desired level under 22 or 23 ft. above the low tailwater, and the length of draft tube required for gradual increase in cross-section can be obtained by carrying it down to the draft-tube pit at an angle to the horizontal or by making a long sweeping curve and carrying it along horizontally until the required length is attained. The location of the height of the generator floor is dictated solely by convenience, and the topography of the ground on which the power station is placed.

The house may be constructed of brick or concrete, it usually being preferable to use the latter material, due to the fact that the equipment for mixing and pouring the concrete is already on the ground, and the work can be carried on by the same gang of men used in building the dam. Where the machinery rests on reinforced-concrete floors, the design of the floors is fixed, not on the basis of their ability to carry weight, but on the maximum deflection under the loadings imposed. Excessive deflection will result in the alignment of the machinery being disturbed. Final alignment of the machinery should not be made until after the forms have been taken out from underneath the floor, and machinery and floor have assumed their final position.

This also applies to the adjustment of the thrust journals for vertical units. The end play in turbines is extremely small and the wheels should be adjusted exactly to their proper relationship with the surrounding gates.

Where vertical units are installed, the hole through the floor, over which the generator sets, should be as large as it is possible to make it and yet give a sufficient bearing surface for the generator frame to rest on, because it is through this hole that the water wheels will have to be dismantled and the parts removed whenever repairs must be made. It is not necessary for the hoisting chains on the crane to be long enough to reach down to the lowest portion of the water wheel, as anything below the floor level may be lifted with sling chains, which are fastened to the part to be removed and are long enough to reach to the crane hook.

The governors may be placed, either on the main floor of the station or down below where the turbines are, if the latter location makes it easier and cheaper to connect them with the gate shafts or shifting rings. It is better, however, to keep all the operating machinery on one floor, continually under the super-

vision of the attendants, except, of course, the water wheels, themselves. The governors are usually driven from countershafts that are geared to the main turbine shaft in the case of vertical units.

Governor countershafts and gearing are shown in Figs. 71 and 72.

Governors for horizontal units are usually driven directly from the main shaft. In some cases the diameter of the shaft is sufficiently great to act as a pulley to drive the governor belts and where the shafts are not large enough for this purpose, pulleys are placed on them.

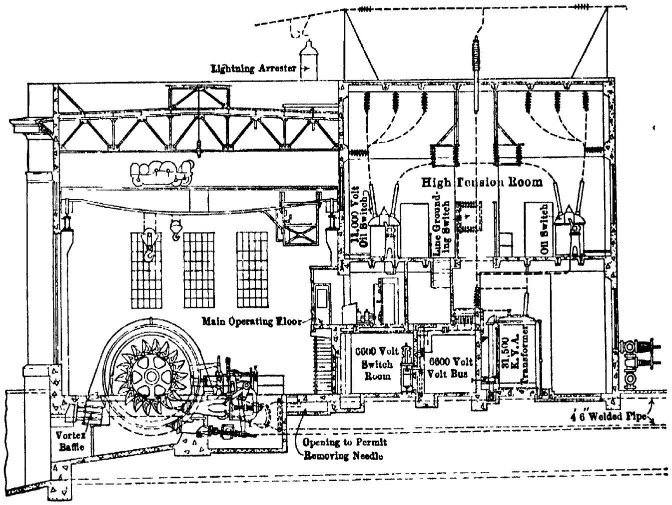


FIG. 73.—Section of power plant. Impulse-wheel driven.

The power house should be only sufficiently wide and high to give a proper housing for the apparatus. The tendency to construct enormous buildings for this purpose is not to be regarded with approval. The height of the power house must be sufficient to permit the hoisting clear of any part of the equipment with the crane, and when this height is reached, there is nothing gained by making the structure any higher. Sixteen to 18 ft. in small stations, and 18 to 22 ft. for large stations, measured from the power house to the lower chord of the roof truss, is usually ample. The clearance between the machines inside the house, and between machines and wall, need never

exceed 4 ft., except where straight shafts are to be pulled out in some direction which would be obstructed by a wall or machine near to it.

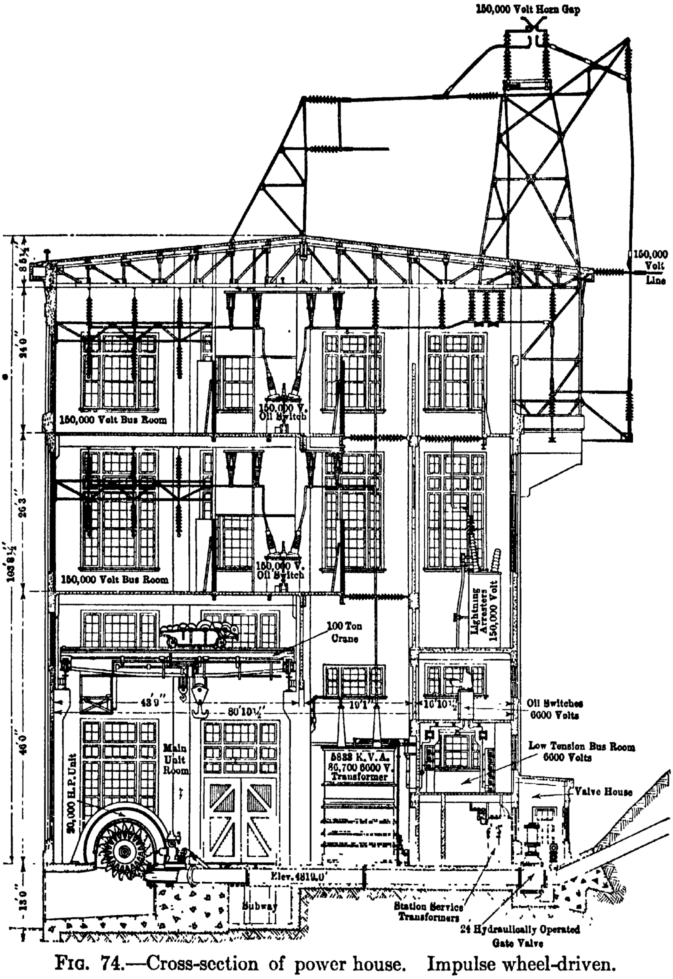


FIG. 74.—Cross-section of power house. Impulse wheel-driven.

In case of horizontal units, it is customary to locate a window in the longitudinal wall opposite each unit, so that the horizontal shaft can be taken out, if desired, together with the generator shaft rotor and the water wheels, these assembled parts coming

clear of the generator frame when the rotor is close against the opposite wall, and that portion of the shaft projecting beyond it, passing through the window.

In case of impulse-wheel driven power stations, the common practice is to locate the wheel inside the house. In many instances the units have only two bearings, one on each side of the generator. The bearing on the side adjacent to the wheel is extended and made considerably longer, and, therefore, has a

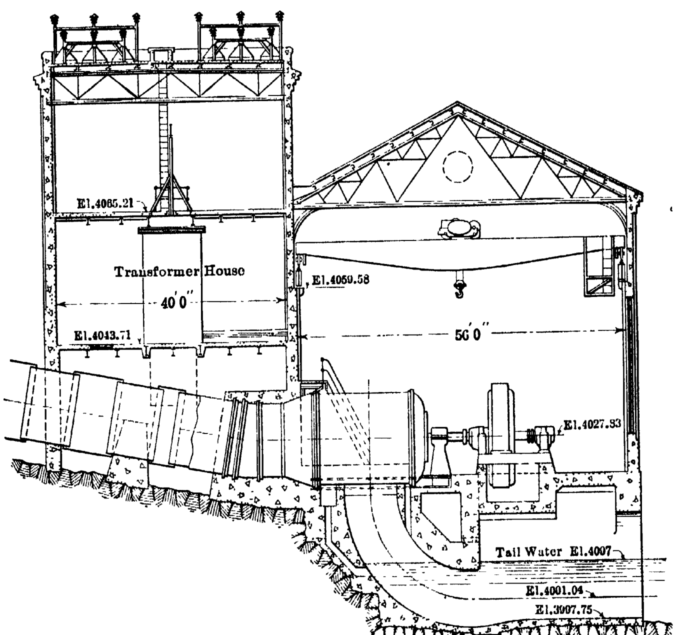


Fig. 75.—Cross-section of power house.

greater bearing area than is customary for a simple generator bearing. Next to this bearing the water wheel is placed on an extension of the generator shaft. While this practice is not approved by some designers, it has been extensively used. Figs. 73 and 74 show cross-sections through power houses for impulse-wheel driven units.

Figures 75 and 76 show two other forms of turbine-driven power stations and, together with the preceding figures, are

indicative of the different methods and views of designers. They all represent approved practice excepting that in some of them the draft tubes drop vertically into the tailrace instead of being curved to discharge the water horizontally in the direction of flow.

It is recommended that designers refer to the current files of the standard engineering periodicals for descriptions of hydro-electric stations and for the reasons which led the engineers to adopt the apparatus and designs which were used in fixing the type and size of plant, and, in this way, become familiar with the practical application of the principles of design.

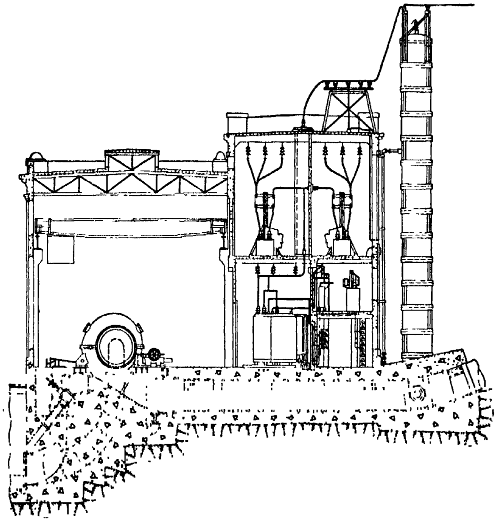


FIG. 76.—Transverse-section of station.

A general criticism of most power houses is that they have been built larger and have cost more than was really necessary.

Power-house floors are almost invariably of concrete and the roof covering of slate, tile, or tar-felt and gravel. The flat, tar-and-gravel roof is the cheapest and is a satisfactory roof.

The roof trusses are made of steel, or of a combination of wood members for compression and steel ones for tension. There is a number of types of roof trusses and it is beyond the scope of this work to enter into a discussion of these various forms. The following, however, give some useful data.

Roof trusses must sustain the load due to the roof, covering, sheathing, snow and wind loads.

The weights of the roofing, per square foot, are, approximately, tin, 1 lb.; corrugated iron, 1 to 3 lb.; slate, 7 to 10 lb.; felt, tar and gravel, 8 to 10 lb.; tiles, 8 to 25 lb.

Sheathing 1 in. thick weighs 3 to 4 lb.

Snow loads vary with the latitude and are commonly taken as follows:

New England and Michigan, 30 lb. per square foot.

New York—Chicago, 20 lb. per square foot.

Cincinnati—St. Louis—Baltimore, 10 lb. per square foot.

Wind loads vary with the slope of the roof. The normal component, acts as a roof load. For a wind pressure equal to 40 lb. per square foot against a vertical surface, the following are the values of the roof loads for various inclinations.

TABLE 4.—WIND LOADS ON ROOFS

5° = 5.1 lb. sq. ft.	25° = 22.6 lb. sq. ft.
10° = 9.6 lb. sq. ft.	30° = 26.5 lb. sq. ft.
15° = 14.2 lb. sq. ft.	35° = 30.1 lb. sq. ft.
20° = 18.4 lb. sq. ft.	40° = 33.3 lb. sq. ft.

The approximate weights of steel roof trusses are given by the empirical formula:

$W = 0.75\, AL\, (1 + 0.1L)$ lb., or

$$W = \frac{C}{45} AL \left(1 + \frac{L}{5\sqrt{A}}\right) \text{lb.} \tag{19}$$

W = total weight of one roof truss.
L = span of truss, in feet.
A = spacing of trusses, *i.e.*, distance between neighboring trusses, c to c measurement.
C = total weight per horizontal square foot of roof.

Value of C is, usually, between 40 and 50.

$$\text{For } C = 45 \quad W = AL \left(1 + \frac{L}{5\sqrt{A}}\right) \text{lb.} \tag{20}$$

The switchboard is preferably placed from 6 to 8 ft., from the longitudinal wall of the station on the opposite side of the house from the generating units, the board being parallel with the longitudinal walls. It is fastened to the floor, in any of the several approved methods, and the top is braced by horizontal

rods which connect with each vertical panel supporting member, and are fastened to the wall. These horizontal supporting rods are usually made of 1-in. standard, wrought-iron pipe, that screw into a clamp connector at the end where it fastens to the vertical supporting member of the switchboard, and on the other end, a flat plate is screwed, which rests against the wall and has one or two holes in it through which expansion bolts can pass, and in this manner the ends are fastened to the wall.

The cables leading from the various machines to the switchboard are sometimes carried in special cable tunnels made in the floors. These are simple trenches, which are formed when the concrete floors are cast, ranging from 4 to 12 in. in width, and 4 to 6 in. in depth. The cables are laid in these trenches and then covered with fine dry sand, which is packed hard, after which a thin covering made of light reinforced concrete slabs is laid on top of the sand, their upper surfaces coming flush with the floor, or checkered iron plates are laid over them. It, however, is better and cheaper to run the cables underneath the floor, supported on iron supports, spaced from 4 to 6 ft. apart. Holes are cast in the floor when it is laid, or later drilled through it, and short sections of iron pipe passed through the holes and grouted in place. The cables pass through these, down under the floor and resting on the iron brackets are exposed so that they can be inspected at any time.

The cables should be heavily insulated with best quality of rubber or varnished cambric insulation, or its equivalent, and triple-braided. A lead sheath outside the insulation gives added protection and its use is recommended.

Care should be taken to cut the sheath away at least 8 in. back from the cable ends, otherwise the system may become grounded. The sheath forms a grounded metallic tube and if its end comes close to a terminal or lug, connection may be established from lug to sheath and in this manner, ground the busbars. These suggestions all apply to conductors carrying less than 15,000 volts. Any interior wires that are subject to greater pressures should be bare, and carried overhead on high-tension insulators. The sizes of wires and cables are usually fixed by the current-carrying capacity instead of the voltage drop, where the length of circuit is under 150 ft. (*i.e.*, 300 ft. of wire).

The following table gives the safe current-carrying capacities of various sizes of insulated wires and cables:

TABLE 5.—SAFE CURRENT-CARRYING CAPACITIES OF INSULATED COPPER WIRES (1913 *National Electrical Code*)

Circular mils	A.W.G.	Table A, rubber insulation (amp.)	Table B, other insulations (amp.)	Circular mils	A.W.G.	Table A, rubber insulation (amp.)	Table B, other insulations (amp.)
1,624	18	3	5	200,000	....	200	300
2,583	16	6	10	300,000	....	275	400
4,107	14	15	20	400,000	....	325	500
6,530	12	20	25	500,000	....	400	600
10,380	10	25	30	600,000	....	450	680
16,510	8	35	50	700,000	....	500	760
26,250	6	50	70	800,000	....	550	840
33,100	5	55	80	900,000	....	600	920
41,740	4	70	90	1,000,000	....	650	1,000
52,630	3	80	100	1,100,000	....	690	1,080
66,370	2	90	125	1,200,000	....	730	1,150
83,690	1	100	150	1,300,000	....	770	1,220
105,500	0	125	200	1,400,000	....	810	1,290
133,100	00	150	225	1,500,000	....	850	1,360
167,800	000	175	275	1,600,000	....	890	1,430
211,600	0000	225	325	1,700,000	....	930	1,490
				1,800,000	....	970	1,550
				1,900,000	....	1,010	1,610
				2,000,000	....	1,050	1,670

NOTE: The current-carrying capacity of bare wires is given in the chapter on "Transmission Lines."

Up to within a comparatively recent time, transformers have been housed, just as the operating machines have been. In most instances they have been placed in extensions of the power house either on the same floor level, or in a story built above the first floor of the power house. Some of the figures showing sections through power stations, show also the location of transformers.

From about 1913, the tendency has been toward using outdoor type transformers, and placing them outside the power house. This practice is more rational than housing them, particularly in the case of high-tension transformers; where the clearances between them and between the connecting wires must be considerable, and this, in turn, requires a great deal of room in any structure built around them. There is no good reason for protecting the transformer from the weather, excepting possibly shielding it from the sun in warm climates. In the southern

part of the United States, where temperatures in the sun reach 135°, the ability of transformers to radiate the heat dissipated in them is greatly diminished, and overheating is apt to result in any except water-cooled units. For such situations some sort of shed should be built over the transformers to shield them from the sun's rays, and if this is not done, water-cooled transformers

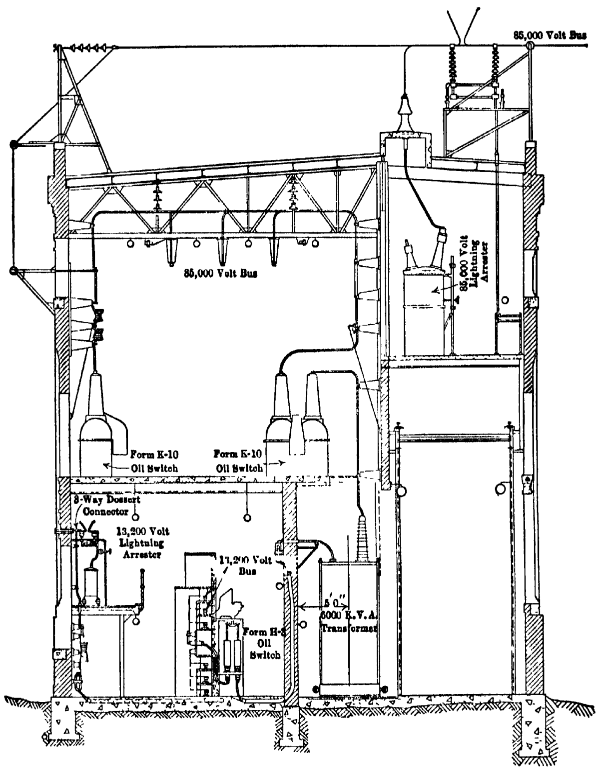


FIG. 77.—Cross-section of transformer house.

must be used, the quantity of water required for cooling being considerably greater than that used under normal conditions.

The transformers are usually set on a platform above ground level, so that they are clear of dampness or any surface water. Choke coils and lightning arresters are placed on a framework constructed around the transformers, and made of either wood or

steel. This method of outdoor installation is more fully described in the chapter on "Substations."

The amount of room required by high-tension transformers and connecting wires is shown in the drawings of sections through power plants at various places in this chapter. The relative cubical dimensions of the generating machinery room and the portion of the house occupied by the transformers and connections in impulse-wheel plants should be observed particularly.

Figure 77 shows a transformer house placed adjacent to a power station, to house the step-up transformers, and from which the transmission lines start.

High-tension Wires.—When the high-tension wires and busbars are located inside the power house, ample clearances between wires of opposite polarities are required, varying from 4 ft. for 30,000 volts to 7 or 8 ft. for 110,000 volts. It was the custom for some years to put the wires and busbars in concrete or brick compartments. Present practice, however, favors the placing of the wires in the upper part of the power station or near the ceiling in the case of a single-story house, and without any surrounding compartments.

They are supported on one of the several available types of insulators. Standard line insulators are frequently used either pin or suspension type according to the voltage between the wires. In some cases, special high-tension post insulators are used.

There is no particularly difficult problem involved in the layout and installation of these wires, provided plenty of space to accommodate them be available.

Brass or copper pipe is being used in many installations, for high-tension busbars and connections. Standard fittings cannot. be used because of the sharp angles and corners on them. All bends must be of bent pipe, and the radius of bend should be at least six times the diameter of the pipe. End connections are made with interior threaded nipples or plugs, the two pipe ends screwing up together to form a smooth butt joint.

Branches require special fittings of a *Y* form, the legs of the *Y* being spread out and rounded in the crotch, so that there is no point at which the radius of curvature, in any direction, is less than that of the pipe.

The transmission line must enter the power station, at some

convenient point, unless the step-up transformers are located outside. A number of different methods of bringing the high-tension wires into the station have been devised. Where the pressure between wires is less than 33,000 volts, the method indicated in Fig. 78 is a good one. As shown, sections of tile drain pipe are set in the power-house wall at the proper elevation, the pipe being placed with its axis making an angle of about 20° with the horizontal so that the entering wire takes an upward direction. This is for the purpose of preventing rain from travelling along the wire into the station. The wire is stretched between

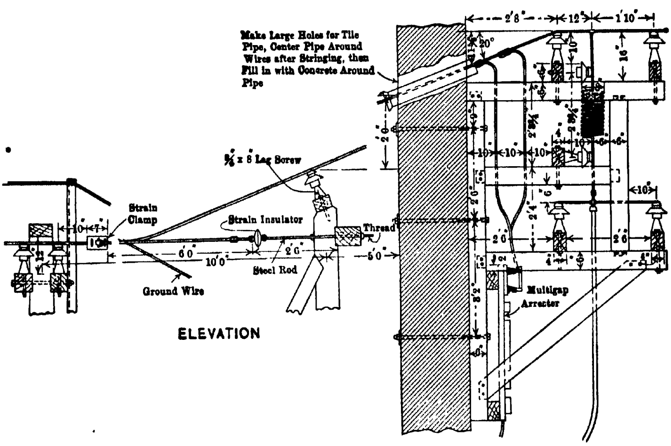


FIG. 78.—Line entrance and interior frame, 6600 volts.

two insulators, one inside and one outside the power house, and, generally, there is no strain on these insulators other than that imposed by the short section of cable between them. While this section is a continuation of the transmission wire, the strain, due to the external forces acting on the transmission line, is taken up on a strain frame outside the building and the stress on the cable, from the holding clamp on the strain frame to the outer insulator, is negligible, the wire simply being bent in an easy curve from clamp to insulator.

A framework must be provided inside the power station to carry the interior insulators. In some cases it is expedient to locate the lightning arresters and choke coils on this interior frame, which form of construction is shown in the figure.

Where the voltage exceeds 33,000, the wires should be brought in through special insulated tubes which pass through the wall, or through the roof, as may be the more convenient. A tube of this kind is shown in Fig. 79, and its application is obvious from some of the cross-sections through power stations shown in the several figures. If the voltage exceeds 66,000 volts, the transmission line should end outside the house and a piece of brass or copper pipe attached to it, having a cross-section of metal equal to that of the cable. The ends of the pipe should be curved or tapered down to the diameter of the wire, the wire passing through the reduced opening thus made and sweated or soldered into place. The joints must be filed smooth so that no sharp edge or corner exists, and the increase in diameter from that of the cable to the diameter of the pipe must be smoothly and gradually made. Increasing the diameter reduces the electrostatic gradient and, therefore, the liability of puncture, or flashing over from the lines, where the tubes pass through the wall or the roof. The pipe diameter should range from 2 in. in the case of 88,000 volts, to 4 in. for 150,000 volts. These pipe sections can be carried through specially made wall or roof insulators just as wires are. This method of increasing the diameter of the conductors at critical points is not much used. It, however, has considerable merit and, with the advent of transmission lines operated at 100,000 volts and more, it is probable that it will ultimately become general practice and the manufacturers of electrical porcelain will provide standard insulating tubes of the larger diameters required.

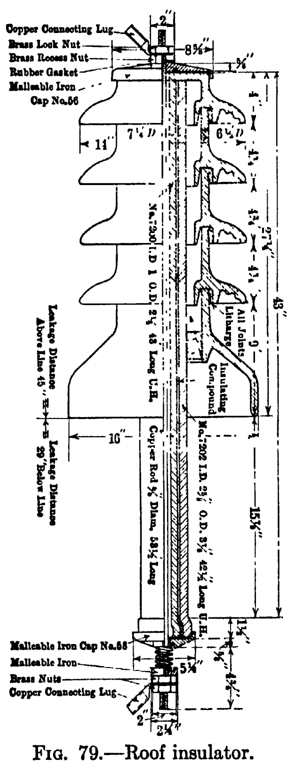


FIG. 79.—Roof insulator.

Other forms of line outlets are shown in Figs. 80 and 81.

Windows and Doors.—In accordance with the general policy of making a power station fireproof, the window and door frames

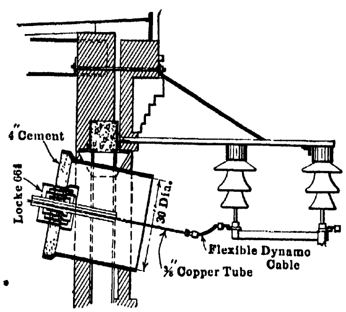


FIG. 80.—Transmission-line outlet.

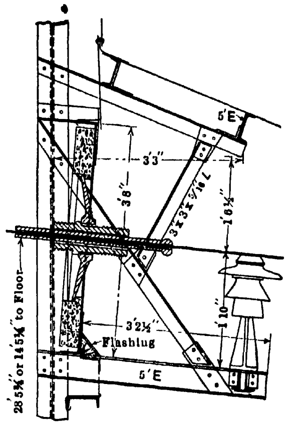


FIG. 81.—Transmission-line outlet.

should be made of metal, the window sash also of metal, and the doors of wood, covered with sheet iron. Stamped-steel, frames

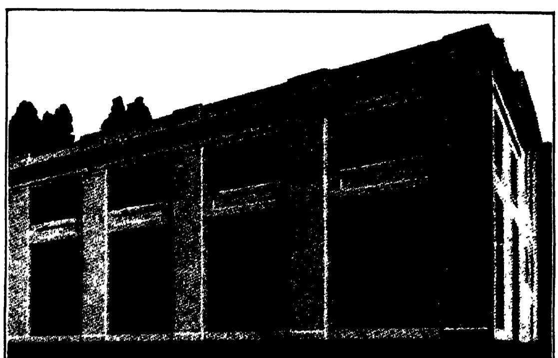


FIG. 82.—Power house of reinforced concrete.

and sash are now available at prices which are but little in excess of those for corresponding wood frames and sash.

One doorway should be large enough to move any piece of

machinery through it, and in case of a large power station, this doorway should be of sufficient dimensions to permit the passage of a railway car over a temporary track laid through it. This doorway is normally kept closed and is only used for the purposes for which it is made.

Ventilation is provided through the windows, these usually being arranged with tilting sections which give a total area of opening equal to 50 per cent. of the window area. This will afford ample ventilation if there is sufficient window area. As a rough approximation, one-half of the wall space should be occupied by window frames. Fig. 82 shows portion of an external view of a power station in which the general height and proportion of the window frames are indicated. There is no occasion for incurring the expense of monitor roofing for purpose of ventilation if the window openings are sufficiently large and numerous.

Lighting.—The power house should be well lighted and provided with numerous outlets along the wall for the reception of plugs so that hand lights can be connected with the circuit whenever it is necessary to inspect the apparatus. Suspended lights from the ceiling can not be used as they would interfere with the movement of the crane. It, therefore, is necessary to use lamps fastened on brackets which are, in turn, attached to the walls. The brackets extend between 3 and 4 ft. from the wall, are spaced from 16 to 20 ft. apart, and an incandescent lamp with reflector is fastened at the outer end of the bracket. The lamps should be 100 to 150 watts, and a 16- or 18-in. mill-type reflector is satisfactory for this service. The reflectors should be set so that they make a slight angle with the horizontal and tend to throw the light toward the center line of the room. The best height of lamps is from 13 to 15 ft. above floor level.

The lighting circuit receives current preferably from the exciter busbars. The station auxiliaries, such as pump or crane motors, should be operated from the power busbars.

Plumbing and Fittings.—The stations must be provided with all necessary comforts and conveniences such as lockers, hand basins and one or more water-closets. The water supply is taken from the penstock or forebay. While these are trivial, they are necessary, and it is easier and cheaper to provide for them in advance of construction, than to try to work them in after the station is completed.

Oiling Galleries and Stairs.—Every part of the plant that requires inspection and every journal that is not inside the waterwheel case must be easily accessible. Small oiling platforms, with narrow iron stairways, should be placed wherever necessary for an operator to reach a journal for inspection or oiling. The platforms may be of mesh-reinforced concrete or rolled checkered plate steel. They cost but little, and contribute to insuring the proper attention of the station attendants to their regular duties of inspection and maintenance of ample oil supply.

Auxiliary Steam Plants.—During seasons of low water, if the load exceeds that which the water can supply, it is necessary to have an auxiliary source of power. The water power is sold at a low rate, and steam power costs much more, per kilowatt-hour, for the amount of energy needed to supply the difference between the delivered power and the amount supplied by the water than the income received from it, but, with an auxiliary steam plant, power can be sold for 365 days in the year, which requires steam operation for only 30 or 40 days per annum. In many cases, power is sold to mills and factories that have steam plants already installed and some arrangement can usually be made whereby these consumers will supply themselves with power during periods of low water, paying for electrical energy during the other parts of the year. In this way the existing steam plants become auxiliaries of the water-power plant without the necessity of any investment and its attendant interest and depreciation. In other cases, it is necessary to install a steam plant in connection with the hydro-electric power station, and, in this event, the size and character of the steam equipment must be settled by the specific local conditions. The plant will be operated intermittently only, while its interest and depreciation charges will go on continuously. Therefore, it should be of the cheapest possible character compatible with giving reliable service. Under these conditions, the question of steam economy is of only secondary importance.

Since it will be in service at occasional and widely separated intervals, the question of a staff of operatives is a serious one. They can not be kept continuously on the payroll, and it is equally impossible to assemble an operative force at short notice for a few days service. It is usually the custom to employ regular station attendants who are also good steam-plant operators and it only becomes necessary to obtain common laborers as firemen,

whenever the steam plant is put in service. This arrangement makes it inexpedient to work more than one shift of men, which, in turn, necessitates a larger capacity of steam plant. The size of the plant is fixed to give a base load of some continuous fixed output, the water-power equipment taking the load peaks. Therefore, the number of kilowatt-hours which a small steam plant can produce each day is very great as compared with the output of the usual steam plant operating on a fluctuating load. For these conditions, the steam equipment must have twice as great a capacity if operated on one shift as it would have if operated on two shifts. The impossibility of giving any definite basis for fixing the size of a plant, without a knowledge of all the other conditions, is obvious. Also, the discussion of steam equipment is beyond the scope of this text. A few general suggestions, however, may be given.

In small-size plants, a successful arrangement has been to extend the dynamo shaft on the side opposite to the water wheel and put a pulley, or rope sheave on it. A jaw-clutch coupling between the water wheel and the generator allows the latter to be disconnected from the water wheel and driven by the steam engine, either by belt or rope drive, depending on the size of the unit. In one or two instances, the engine shaft has been direct-connected to the generator shaft through a large clutch coupling, so that the generator would run as a steam-driven, direct-connected unit, or as a water-wheel driven unit, as occasion might require. In large power stations, it is cheaper to install steam-turbine equipment complete, than to use reciprocating engines arranged for connecting with the water-wheel generators. When this is done, the steam-driven units are usually placed in an extension of the power house or in a separate power station near the water-power plant on the river bank. In case of plants feeding very long transmission lines, it is sometimes better to install the steam auxiliary at the substation at the load end of the line. In any case, this auxiliary plant should be so located that it may be supervised by attendants who are regularly and continuously employed.

Tests.—The usual tests which are made on a completed power station are:

1. Test of turbine efficiency.
2. Test of maximum power of the water-wheels.
3. Heat test of generators.

4. Regulation test of governors.

In order to make these tests with any reasonable cost and attain accurate results without waste of time, it is necessary to make proper preparation for them. Makeshift arrangements result only in loss of time and money and produce but uncertain results.

The only practicable methods of loading the water wheels are either by means of the generators themselves, or the Alden brake. While these brakes may be obtained for tests at a reasonable rental, it is expensive to ship them to the point of trial and install them in connection with the water wheel as this requires the removal of the generator. The Alden brake, therefore, is to be regarded as a last resort, to be used only when there is a serious dispute between the engineer and the water-wheel builders as to the efficiency of the wheels which involves a large financial consideration. The universal way of loading the wheels is by means of the generators. These must be tested in the shop and the efficiency at all loads fully known. There are facilities for making the complete electrical tests of generators in every electrical manufactory, and the machine should be tested there before shipment, in the presence of the engineer or his representative, and the water-wheel manufacturer should have a representative present, so that the results of the tests will be agreed on by all parties concerned. There is no way in which the efficiency of the generators can be determined after they leave the factory except by disconnecting from the water wheel and driving them at various loads with an electric motor which itself has been previously tested and the efficiency of which is known. This, while not impossible, is impractical.

The load for the water wheel and generator must be steady, variable at will within the limits of half load to the maximum possible output of the unit, which is usually 125 per cent. load, and, preferably, non-inductive. The best means, and the ones universally used, are water rheostats or submerged iron-wire resistances.

Rheostat for Test Loading.—Rheostats for absorbing the full-load energy of a generator, may be of two kinds, one being the well-known "water rheostat," in which the liquid forms the resistance and energy absorbing medium. The other, is the submerged iron-wire rheostat, in which the resistance is made up of iron-wire coils. The wires have a small cross-section and are

prevented from melting under the high-current densities, by being submerged in water.

The water rheostat is usually made up of a number of barrels filled with water up to within 6 in. of the top. The resistance of the water is reduced by the addition of a little salt or sulphuric acid. This must be added to the liquid cautiously as very slight amounts cause comparatively great changes in resistance. The amount required for any test must be determined for the specific conditions. The electrodes are made of wrought-iron pipe of any size between 2 and 6 in. in diameter, there being two pieces of pipe in each barrel. These electrodes are suspended from sash cords passing over the pulleys above the barrel, so that they may be raised or lowered and, thereby, immersed to a greater or less extent in the liquid. A metallic coupling or a piece of heavy wire should be inserted somewhere in the length of the cord so that the latter may not become saturated over its entire length by capillary attraction. By raising or lowering the electrodes the resistance may be increased or diminished and the load on the generator varied. The liquid will heat with passage of the current, and as it heats its resistance diminishes. It, therefore, should be allowed to warm up before beginning the test. The number of barrels and electrodes required depends on the energy which they must absorb. About 50 kw. per barrel or equivalent volume is within the limit of good practice. Fig. 83 shows connections of a rheostat of this kind for loading a three-phase generator. The electrodes in the barrel must be moved until the current is the same in each phase. Where the water is naturally slightly alkaline and the voltage of the generators is high—say 6600 volts—there is no need of adding either salt or acid to the water, and as much as 200 to 300 kw. of energy may be dissipated in each barrel if a small stream of water is fed continuously to the barrels through a rubber hose.

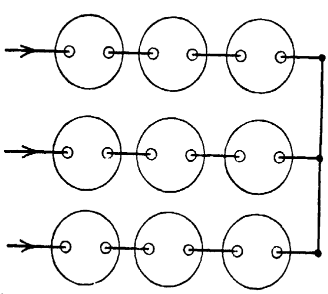


FIG. 83.—Arrangement of water rheostats for 3-phase circuit.
(3 barrels in series on each phase, vary number per phase, to accord with generator voltage.)

The iron-wire rheostat is simply a series of coils of iron wire

having a resistance such that when in series only about one-half the normal-load current of the generator can pass through them. These coils are quickly and cheaply made by winding them in a lathe around a 2- or 2½-in. iron pipe as a mandrel. The coils are then placed in barrels or tanks. If placed in barrels, they may be wound helically, from top to bottom around the inner surface and held against the side of the barrel by staples. If placed in tanks, which are shallow wooden boxes, reasonably water-tight, they are strung back and forth from end to end of the box. Two or three layers of coils may be placed in each box. If the box is longer than 3 ft. there should be a middle support, which is simply a wooden crossbar under each layer of coils at their middle point, to keep them from sagging. The horizontal clearance of the coils should be about 2 in. and the vertical clearance about 4 in. There is one resistance provided for each phase and, preferably, each resistance unit should be in a separate tank or barrel.

The author is aware of the fact that many successful tests have been conducted with iron-wire resistances strung on frames and submerged in the forebay or tailrace. While this practice is satisfactory for streams in which the waters bear no natural salts in solution, the writer has failed in several instances, to obtain anything but short-circuits from resistances immersed in the stream. Wooden boxes which serve as tanks, are inexpensive, allow immediate inspection of the resistances without removing them, and, generally, will cost no more than the frameworks and lifting apparatus required for immersing in streams. As an example, three boxes, each 4 ft. wide, 6 ft. long and 2 ft. deep made of ordinary, 1½-in. lumber, and supported on 6 by 6 in. sills laid on the ground, will effectually cool resistances absorbing 2000 kw. at 6600 volts. A rubber hose feeding a 1½-in. stream of water to each box is sufficient to keep the water cool. The size of the submerged iron wire to carry a given current is fixed by the following formula:

$$d = kI^{2/3} \tag{21}$$

$$l = \frac{d^2E}{112I} \tag{22}$$

d = diameter of wire, in *mils*.

I = current in amperes. This, for three-phase currents, is the number of amperes *per phase*.

E = voltage. For three-phase currents, E = *Volts between phases*
l = length of wire required, in feet
112 = average resistance per mil-foot of iron wire at 120°F.
k = a constant, varying from 2.75 to 3.25. 3.00 is a good average value.

The size of the coil must be computed for the maximum overload on the generator and the length of the coil must be such as to give it total resistance to limit the current flow to one-half its normal value. Switches must be provided by which proportionate parts of the coils can be cut out, so that loads of 50 per cent., 75 per cent., 100 per cent. and 125 per cent. of normal can be obtained.

Instruments.—The switchboard instruments can not be used for a test. The instruments used must be calibrated in connection with their potential and series transformers. Complete testing outfits may be obtained at reasonable rental from several sources. The cost is small, disputes are eliminated and, in addition, the switchboard instruments may be tested incidental to the generator tests. The instruments necessary, comprise: Two wattmeters, one voltmeter, and two amperemeters. A power-factor meter is a convenient instrument to have but not essential. The power measurement is made by the two-wattmeter method. The wattmeter connections are as indicated in Fig. 84. The total generator output is equal to the sum of the two readings of the wattmeters. The current and voltage from the exciter should always be observed as a matter of record.

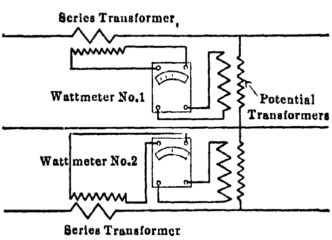


FIG. 84.—Connections for 2-wattmeter power measurement, 3-phase circuit.

The efficiency tests of generators include the net energy of excitation but take no account of the efficiency of the exciter itself. Therefore, if the exciter is driven from the water wheel, it should be disconnected and, the generator excited from some other source, unless the efficiency of the exciter is known, in which case, the total load on the wheel is the generator plus the exciter load.

The quantity of water passing through the turbine is measured by a weir constructed in the tailrace, a hook gauge being used to determine the water levels. The weir measurements should be checked by Pitot tubes in the tailrace. A stake should be driven near the edge of the forebay or at some convenient point in the lake and a steel scale fixed to it, about one-half the scale being submerged. The difference in level between the top of the scale and the reference point on the hook gauge in the tailrace, should be established by an accurate survey with a "Y" level. Only occasional readings on the lake-level scale are necessary as this will remain constant over a considerable period of time. Knowing the difference in level between the two reference points, the actual difference can be determined from the readings of the hook gauge and of the lake level on the scale on the stake. The head from the middle point of the water wheel to the reference point on the hook gauge, should also be measured. In the case of a single vertical wheel, the elevation of its middle point will be at approximately the middle point of the gates. If the unit is made of a pair of vertical wheels, the middle point will be located halfway between the two wheels, if the two wheels have a common discharge. If the two wheels have separate draft tubes, each must be treated as a single vertical wheel. In the case of a horizontal unit, the middle point is the elevation of the center of the shaft. This measurement gives the head due to the draft tube.

A pressure gauge should be connected with the wheel casing, the connection being made at any convenient point or height. The elevation of the gauge itself, however, must be at the middle point of the wheel. A vacuum gauge should be connected with the draft chest, the elevation of the gauge being the same as that of the pressure gauge. The gauge pipes on the interior of the turbine case and the draft chest should be set perpendicular to the casing wall, so that the flow of the water is parallel to the end of the pipe. The sum of the readings of these two gauges should give the net head on the wheel, and the net head thus determined should check within 1 per cent. with the net head computed by deducting the loss in head due to entry (exclusive of velocity head) plus the friction loss in the penstock, from the total head.

A reliable tachometer is convenient but not necessary. A good speed counter with a stop-watch is sufficiently accurate. Temporary telephone connections should be made from the

instrument bench to the load rheostat and to the hook gauge unless these points are within 100 yd. of the bench and may be easily seen from it. Light must be provided for the instruments, because tests sometimes run continuously for 18 hr. or more. The staff required usually comprises:

The Chief of Test and such observers as may be present from the manufacturing companies interested.

One assistant to read instruments.

One assistant at the switchboard.

One assistant at hook gauge and Pitot tubes in the tailrace.

One assistant at the headgates who will also take lake-level readings.

One watchman at the load rheostat to report if any unusual steam or flashing appears.

After preparing, a continuous run of 3 or 4 hr. at full load should be made to bring the machinery and water in the load resistances up to a temperature, and to be sure that the plant is working smoothly.

Prior to beginning tests, a number of log blanks should be prepared. These are sheets divided into vertical columns and each column given its proper title under which the records taken are set down. The following is a list of titles and the columns in the log blanks should be arranged in substantially the same order, horizontally. Those which have a star opposite them are not filled in by any records but are the results computed from the readings. They are placed in the order given because it is convenient to so locate them.

Hydraulic Observations

1. Number of run.
2. Time.
3. Lake-level scale.
4. Hook gauge.
*5. Total head.
*6. Head on weir.
*7. Discharge by weir.
8. Pitot-tube reading.
*9. Discharge by Pitot tubes.
10. Pressure gauge.
11. Vacuum gauge.
*12. Total head by gauges.
*13. Entry plus friction head.
*14. Net head by deduction.

ELECTRICAL OBSERVATIONS

1. Number of run.
2. Time.
3. Speed of unit.
4. Volts between phases.
5. Current per phase.
6. Power-factor meter.
7. Wattmeter No. 1.
8. Wattmeter No. 2.

*9. Generator output by volts and amperes. (This equals $1.732EI\phi$, I being the amperes in one phase, E = volts, ϕ = power-factor)

*10. Output of wattmeters.

*11. Generator efficiency at load. (This taken from efficiency curve of generator.)

*12. Horsepower delivered to generator shaft.

13. Temperature of room.
14. Exciter volts.
15. Exciter amperes.
16. Volts at field terminals of generator.

*17. Exciter kilowatts to generator.

The fixed observations which are made at the beginning of the test are: barometer, and temperature of outside air.

The heat test of the generator is made by running it for 2 hr. at its maximum overload, then for 6 hr. at normal load, after which it is stopped. Immediately after machine stops, thermometers should be fastened against one of the field windings and against one of the armature windings by soft putty and allowed to remain from 3 to 5 min. Where possible, the bulbs of the thermometers should be pushed inside of the armature winding slots.

The following formulæ are convenient in computing the results:

Call kw. the total generator output in kilowatts.

$$\text{Net hp. of turbine} = \text{hp.}_n = \frac{\text{kw.} \times 1.34}{E} \tag{23}$$

E = generator efficiency at given load

$$\text{Gross hp. in water} = \frac{h_n Q}{8.8} = \text{hp.}_g \tag{24}$$

h_n = net head

$$\text{Turbine efficiency} = \frac{\text{hp.}_n}{\text{hp.}_g} \tag{25}$$

Efficiency of unit from water to generator terminals is

$$\frac{1.34\ \text{kw.}}{\text{hp.}_g} \tag{26}$$

CHAPTER VI

WIRES AND CABLES

Wires and Cables.—The metals used for transmission conductors are copper and aluminum. Copper has a higher conductivity per unit of cross-section and length than aluminum, but aluminum has the higher conductivity per unit weight of metal for a given length.

The characteristics of these two metals are as follows:

TABLE 6

	Copper	Aluminum
Resistance per cubic centimeter	1.7213×10^{-7} ohm	2.78×10^{-7} ohm
Resistance per cubic inch	0.6776×10^{-7} ohm	1.0945×10^{-7} ohm
Resistance per mil-foot	10.4 ohm	16.8 ohm
Resistance per meter-gram	0.15328 ohm	0.247 ohm
Temperature coefficient of electrical resistance	0.003875	0.0022
Specific gravity	8.89	2.68
Weight per cubic inch	0.321 lb.	0.097
Weight per mil-foot	321×10^{-8}	91.5×10^{-8}
Tensile strength per square inch	30,000 to 60,000 lb.	20,000 to 30,000 lb.

All above for metals at 20°C. Commercial copper conductivity about 97.8 per cent. of above values.

Aluminum.—From the preceding table it is seen that the volume of aluminum required to give a conductivity equal to a certain copper conductor, having a fixed length is 1.616 times the volume of the copper, or 61.6 per cent. more of aluminum than copper is required to give the same resistance.

The weight of a given volume of aluminum is 30.2 per cent. of that of an equal volume of copper. Hence, the weight of aluminum for a given conductivity is $1.616 \times 0.302 = 48.8$ per cent. of the weight of the copper, having the same conductivity.

Copper has but few advantages, as compared with aluminum, and these are negligible when the lower cost of aluminum is

considered. For equal costs of transmission material, over twice as much per pound, can be paid for aluminum as for copper. Manufacturers of aluminum, usually, vary the selling price of that metal in accordance with the fluctuations in copper prices, keeping it at such a value as to make it cost about 23 per cent. less than the equivalent copper, which is a compelling factor in the selection of the metal to be used.

During the years 1911 to 1915, the price of aluminum cables has been between 23 and 25 cts. per pound.

The advantages of aluminum over copper, briefly, are:

1. Its lower cost.

2. The greater diameter of the wire for a given resistance, or given cost. This tends to reduce the corona effect on high voltages, as is elsewhere explained, and also, the better radiation gives a lower temperature under load, thereby, slightly, reducing the conductor resistance. Besides, a better mechanical tie can be made at the insulators, than on a smaller copper wire.

3. The surface of aluminum oxide appears to shed sleet better than does copper.

4. Due to its lightness, freight charges and the cost of distributing along the line on reels are lower.

The disadvantages of aluminum as compared with copper are:

1. It can not be soldered.

2. Nearly all electrical fittings being of copper, there must be connection at certain points between the aluminum conductors and the copper fittings. A good joint between them is difficult to make and, unless well made, electrolytic action may, ultimately, cause failure of the joint.

3. It is soft and easily abraded if dragged over stones or hard substances, and, therefore, it has to be carefully handled in the field.

4. The lower cost of aluminum does not appear as an actual saving except for lines having short spans—say 250 ft. or less. The elastic limit of aluminum and its modulus of elasticity are lower than those of copper, while its change in length with temperature is greater. Hence, for a given clearance between the ground and the wire, with maximum sag, the supporting poles or towers must be higher if aluminum cables are used than would be necessary if they were of copper.

Since the cost of the towers or poles increases very rapidly with increase in height, the total cost of a line, having aluminum conductors, may equal, or even exceed, that of a line having copper conductors, though the cost of the aluminum cables may be considerably less than the cost of copper conductors.

For these same reasons, aluminum is not adapted for lines in which the spans are great and the cables small, because they sag so greatly under high temperatures and are stressed so little that they will "snake" or whip under sudden gusts of wind, which means that all the cables on a pole do not sway together, preserving their normal separation, but whip about individually, thus tending to come near enough together to produce corona or even actual contact, and consequent short-circuiting.

These objections have been largely overcome by making aluminum cables with steel cores.

The advantages usually outweigh the objections so that aluminum is now being used to a considerable extent for transmission lines.

The Aluminum Co. of America has perfected and is marketing a number of fittings, connectors and other accessories that make the construction of an aluminum line as easy and simple as that of a copper one.

Joints.—For straight line joints the dovetail splice, when properly made, is satisfactory. This is illustrated in Fig. 85 and is made by opening the ends of the cable to be joined, fitting the strands of one between those of the other and wrapping one strand at a time tightly round the others and the cable which they surround.

Compression joints are generally used on sizes of cable from 2/0 B. & S. up. They are of two forms, namely the three-piece and the single-piece. The three-piece joint is shown in Fig. 86. It consists of two cast-aluminum sleeves bored to fit the cable and provided with bosses which are pressed down to the diameter of the sleeve by hydraulic pressure, compressing all strands of the cable to form practically a solid section. The ends are threaded right and left hand, and united by a similarly threaded stud. These joints are put on in the factory, the sleeve which is threaded right hand being invariably put on the end of the cable that is on the inside of the reel.

Thus, in erecting the cable, the left-hand threaded sleeve, which is on the outer end of the cable, is pulled off one reel to the

reel that is ahead of it along the line and is connected by the stud to the inside of the cable on the second reel after this cable is pulled out.

The single-piece compression joint is similar in form but of one piece and is put on in the field, a suitable hydraulic press and pump being provided for the purpose. The ends of the cables to be joined are brought together in the middle of the sleeve which is then compressed. A finished joint of this kind is shown in Fig. 87. These joints are very efficient, both mechanically and electrically.

FIG. 85.—Dove-tail joint.

FIG. 86.—Three-piece joint.

FIG. 87.—Compression joint.

FIG. 88.—McIntyre joint.

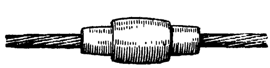


FIG. 89.—Wedge joint.

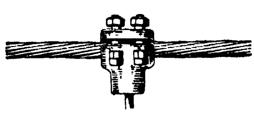


FIG. 90.—Tap-off clamp.

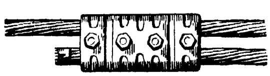


FIG. 91.—Parallel groove connector.

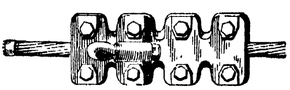


FIG. 92.—Strain clamp.

The joints are made in the field by means of a portable hydraulic jack and dies. The weight of these tools is about 200 lb., the largest piece weighing about 150 lb.

The McIntyre joint, Fig. 88, is used chiefly on the smaller sizes of cable, though it has been used on sizes as large as 650,000 c.m. Like the compression joint, it is both mechanically and electrically efficient. It is made of seamless drawn aluminum tubing, oval in section, into which the ends of the cables to be joined are pushed side by side from opposite ends of the sleeve, after which, the joint is completed by giving the sleeves three twists, the ends of the sleeves being held in splicing clamps.

The wedge joint, Fig. 89, is designed primarily for use on larger sizes of cable than 2/0, in emergencies, being a form of joint that can be quickly made up. It consists of two cast-aluminum sleeves, bored conically on the inside, the strands of the cable being forced out against the conical surface by driving a cone over the center strand. A right- and left-hand threaded thimble screws over the two sleeves and pulls them together.

This joint depends upon tension for its electrical efficiency and should not be used in places where cable hangs without tension, and its use is not recommended, excepting for emergencies.

Two forms of joints are provided for making tap connections. The tap-off joint, Fig. 90, is made in two pieces to clamp over the main-line cable. The tap wire is sweated into the lug, which is bored to fit the tap wire and tinned ready for solder before leaving the factory. In the field it can be handled like a tinned copper lug, and a wire sweated into it in the usual way.

The parallel groove connector, Fig. 91, is designed for use where a joint is required to transmit the full carrying capacity of the main-line cable, or for connecting jumpers to the main line, or making a connection at the end of a line to a power house or substation. It is of two pieces, grooved to fit the cables to be connected, and bolted together over the two cables. When one cable is of copper, the groove for it is copper bushed, the bushing being sweated into the groove in the factory.

For dead-ending at the end of a line or at points along the line, the dead end or strain clamp, Fig. 92, is furnished. It has been designed to give sufficient bearing on the cable, when clamped over it, to develop the full strength of the cable. Eye-bolts are provided for attaching it through messenger wire and strain insulators to the pole or crossarm.

The bolts used in the above three forms of joints are galvanized and a galvanized lock washer is used under all nuts, so that once set up there is no chance of their becoming loose.

Bimetallic Wires.—Both copper and aluminum cables are made with steel cores to give added strength. This arrangement is not so necessary for copper cables, but for high-tension lines on towers with long spans it is almost essential to reinforce aluminum to compensate for its high coefficient of expansion and its low elastic limit. The electrical characteristics of bimetallic wires are:

Resistance, copper and steel wire.

$$R_1 = R_c + [r_1^2 \times 57{,}275 \times 10^{-9}] \text{ ohms per foot length.} \qquad (27)$$

R_c = resistance of copper cable having same diameter as compound cable.

r_1 = radius of inner steel core in inches.

Resistance, aluminum and steel wire.

$$R_2 = R_a + [r_1^2 \times 51{,}128 \times 10^{-9}] \text{ ohms per foot length.} \qquad (28)$$

R_a = resistance per foot, of aluminum cable having the same diameter as the compound cable.

The inductance does not differ appreciably, from that of an all-copper or all-aluminum wire having the same diameter and distance of separation from its neighboring wire, provided the distance of separation be 30 in. or more.

Physical Properties of Compound Wires.—The weight of a copper wire having a steel core is

$$W_1 = W_c - 1.4756r_1^2 = W_c - 0.369d^2 \text{ lb. per foot.} \qquad (29)$$

W_1 = weight per foot length.

r_1 = radius of core in inches.

d = diam. of core in inches.

W_c = weight per foot length of an all-copper wire having the same outside diameter as the compound wire.

The general formula for weight of wire is

$$W = \pi[(r_1^2S_1 + (r_2^2 - r_1^2)S_2] \text{ lb. per foot.} \qquad (30)$$

which for any two metals reduces to

$$W = W_x + r_1^2\pi(S_1 - S_2) \text{ lb. per foot.} \qquad (31)$$

r_2 = radius of outer shell, or tube of wire, in inches.

S_1 = weight per foot length of metal forming the core having a cross-section of 1 sq. in.

S_2 = weight per foot length of one square inch of metal forming the shell.

W_x = weight per foot of solid wire all of the same metal as the shell and having a diameter equal to that of the shell.

For aluminum and steel this reduces to

$$W_2 = W_a + 7.057r_1^2 \text{ lb. per foot.} \qquad (31a)$$

W_a = weight per foot of solid aluminum wire of same diameter as compound wire.

Example. Take a 0000 B. & S. gauge wire of aluminum and steel.

Diameter of core $= d_1 = 0.3$ in.

$r_1 = 0.15$ in.

W_a from table $= 0.195$ lb. per foot length.

$7.057 r_1^2 = 0.0225 \times 7.057 = 0.15878$

$W_2 = 0.195 + 0.15878 = 0.35378$ lb. per foot.

Strength of compound wire

$$H = H_x + \pi r_1^2 (U_1 - U_x) \tag{32}$$

H = ultimate strength of wire in pounds.

H_x = ultimate strength of a wire made of same metal as that of shell material and having same diameter.

U_1 = ultimate strength of 1 sq. in. of steel wire.

U_x = ultimate strength of 1 sq. in of metal, of which shell is composed.

Thus, for the aluminum-steel cable of dimensions given in the preceding example, the ultimate strength would be

$H_x = 0.1662 \times 30{,}000 = 5000$ in which 0.1662 is the area of a No. 0000 cable in square inches.

$H_c = 5000 + \pi \times 0.0225\ (100{,}000 - 30{,}000) = 9{,}950$ lb.

The elastic modulus of a compound wire is

$$M_c = M_2 + \left(\frac{r_1}{r_2}\right)^2 (M_1 - M_2) \tag{33}$$

M_2 = elastic modulus of shell.

M_1 = elastic modulus of core.

Reels.—Wire and cables are usually shipped on wooden reels, which are returnable to the manufacturer. The quantity of different size wire and cables, which are usually wound on a single reel, are given in the following table:

Cable and Wire Carrying Capacity of Standard Reels
(General Electric Co.)

Over-all dia. of cable, in.	Reel No. 6 24×12×12	Reel No. 5 30×21×15	Reel No. 4 48×24×26	Reel No. 3 60×24×34	Reel No. 2 60×41×34	Reel No. 1 66×41×34
	Maximum Length of Wire or Cable, per Reel, Feet					
0.25	1,500	5,500	9,000			
0.30	1,050	3,900	8,000			
0.35	790	2,850	7,000			
0.40	600	2,075	6,000	9,700		
0.45	480	1,675	5,000	7,500		
0.50	365	1,375	4,000	6,100		
0.55	260	1,100	3,400	5,100	9,900	12,400
0.60	240	890	2,930	4,400	8,300	10,400
0.65	220	785	2,430	3,700	7,150	8,900
0.70	165	650	2,120	3,180	6,100	7,600
0.75	145	580	1,760	2,650	5,200	6,500
0.80	...	550	1,460	2,200	4,400	5,500
0.90	...	410	1,180	1,780	3,580	4,470
1.00	...	300	1,000	1,500	3,000	3,750
1.10	...	...	830	1,250	2,500	3,120
1.20	...	...	730	1,100	2,200	2,750
1.20	...	...	600	900	1,750	2,180
1.40	...	...	530	800	1,600	2,000
1.50	...	...	430	650	1,300	1,620
1.60	...	...	...	550	1,100	1,370
1.70	...	...	...	490	1,000	1,250
1.80	...	...	...	420	850	1,060
1.90	...	...	...	400	800	1,000
2.00	...	..	...	375	720	900
2.25	...	...	...	270	550	690
2.50	...	...	...	220	460	570
3 00	...	...	...	165	360	450
	Approximate Maximum Weight of Cable, per Reel, Pounds					
	175	500	1,500	2,500	5,000	6,250
	Approximate Weight of Reel with Slats, Pounds					
	36	100	240	495	650	760

CHAPTER VII

INSULATORS

Insulators for high-tension power transmission are now almost invariably made of porcelain although some glass insulators are used. A few lines have been equipped with insulators made of "Electrose" which is a patented composition. These are more satisfactory than porcelain because they are lighter and not so susceptible of mechanical injury due to shock or electrical discharge, as porcelain. They are, however, more expensive. The production of an insulator which will resist the high voltages of the lines which they support presents no little difficulty. It is not, however, normal line voltages which fix the necessary dielectric strength of the insulator. Transmission lines are subject to transient potentials, which are very high as compared with the normal line voltage and the frequency of which may be many thousand cycles. In some tests made by Imlay and Thomas, in 1912, it was discovered that insulators which successfully resisted the application of 240,000 volts at normal frequency of 60 cycles per second failed under the application of slightly over 100,000 volts when subjected to high-frequency voltage. From these considerations it follows that the design and dielectric strength of an insulator must be fixed to resist these transient high-frequency voltages which proceed from surges on the line, and not based on the line voltage and frequency only.

In addition to the electrical resistivity of the insulator, it must be strong mechanically. The discussions, elsewhere in this work, of sag and stresses in transmission lines show how great the mechanical forces are which act on the supports, and that the insulators must be amply strong to resist even abnormal forces which may be applied to them and without undergoing any mechanical injury. An insulator which is cracked or, in any wise, injured mechanically becomes useless electrically.

It is important to note that insulators which are amply strong mechanically may be easily cracked if mounted on pins which are

not strong enough to resist the strain, and bend slightly under a heavy pull. Bending of the pin will crack an insulator which otherwise would be quite strong enough for the purpose. It is usually safer to purchase both insulator and pin from the same manufacturer with a guarantee of mechanical strength for the complete unit.

There are two general varieties of insulators, one being the well-known form which is supported on an upright pin fastened to a crossarm and known in the trade as the "pin-type insulator" while the other is the suspension insulator which is made up of a series of porcelain disks flexibly connected together so that they form a "string," the axis of the string being the center line through the disk. These are made in a number of different designs which depend partly on the conditions to be met and partly on the personal views of the designer.

Pin-type Insulators.—Pin-type insulators are made up of one or more porcelain bells, or skirts, as indicated in Figs. 93, 94

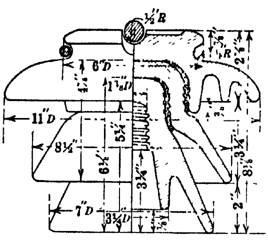


FIG. 93.—Porcelain insulator 45,000 volt circuit.

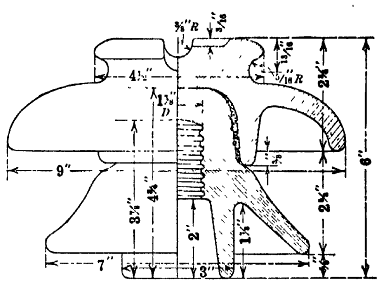


FIG. 94.—Porcelain insulator.

and 95. In the top is a groove to receive the transmission wire, while just below the top is a neck in which the tie-wire lies. The bells are hollow and are screw-threaded inside so that they may be screwed on to the insulator pin. This practice has been modified, however, by cementing an iron thimble into the insulator, which thimble is threaded to screw on to the stud of the iron insulator pin.

The size of the insulator, that is the diameter, and number and radial length of the bells, is fixed by the voltage to which it is to be subjected. The greater the radial distance from the wire to the bottom of the bell, measured along its upper surface and then

radially back on its under surface to the pin, the greater is the resistance to leakage and arcing because of the length of the leakage path. If, however, the bell is made great in diameter in order to produce a long leakage path, the object is partly defeated by the fact that the area for leakage is increased in a corresponding ratio. Therefore, a wide flat disk does not possess as good insulating qualities as a steep-sided cone of small diameter. These conditions, together with the fact that it is desirable for the insulator to shed water constitute some of the reasons for the forms of insulators now in use.

Its form also results from spreading the bells as far apart as possible to reduce the potential gradient. The several bells, together with the insulator pin, constitute a series of condensers. If the bells approach close to each other, and the inner bell close to the pin, the capacity of the condensers is comparatively great and an appreciable capacity current will flow over each insulator. Also, the potential gradient of the air, lying between adjacent bells, becomes greater with the nearer approach of the bell surfaces to each other, and thereby the insulator is more susceptible to puncture and flash-over. Hence, the bells are designed to have as great a space between them as practicable, and to keep all bells as far away from the pin as possible.

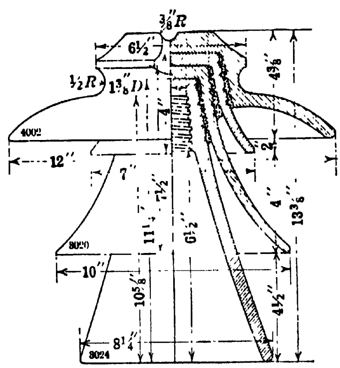


FIG. 95.—Porcelain insulator.

Another essential element of design is to have the electrostatic stresses distributed as uniformly as conditions will permit and avoid setting up high stresses at some particular point on the bells. It has been suggested that an insulator having the topmost bell made of metal would be better and cost less than an equivalent insulator made wholly of porcelain. Good theoretical reasons exist for this suggestion and it is possible that insulators of this kind may become commercial devices.

In the usual pin-type insulator, the upper bell is not coned as much as the lower ones, but is more disk-shaped. This is for the purpose of providing a long arcing path whenever there is a

tendency for the current to jump from wire to insulator pin, passing successively from bell to bell, until the pin is reached as indicated in Fig. 183.

These general statements cover only superficially, a few of the considerations which govern the insulator design. Design and manufacture of insulators are complex, as not only are the questions of shop and electrical conditions involved, but the whole art of ceramics enters into it, so that it is quite impossible to discuss here anything more than the requirements which the purchasing engineer should insist on.

Wherever more than one bell, or skirt, is required, it is customary to make the insulator in separate sections, each section carrying

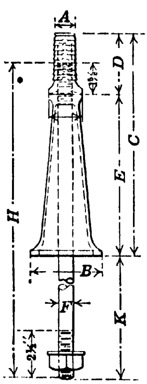


FIG. 96.—Iron cross-arm pin.

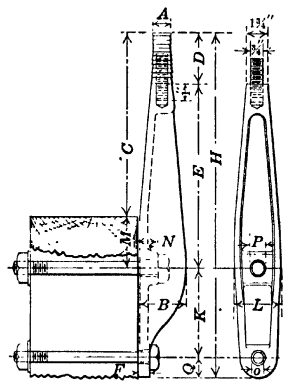


FIG. 97.—Malleable iron-pole top pin.

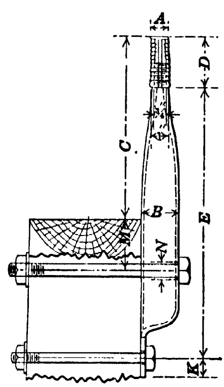


FIG. 98.—Pole top pin made from standard 2-inch pipe.

its bell, and these nest one inside the other and are firmly cemented together as shown in the figures.

In general, the design of pin-type insulators is based on 12,000 to 20,000 volts per individual section, or bell, the average being 15,000 volts per bell, so that for 45,000 volts, the insulator would be made up of 3 bells and for 60,000 volts the number of bells would be four.

The length, from wire to pin, measured over the surfaces—upper and lower—of the bells is approximately 0.8 in. per 1000 volts, for insulators for pressure above 5000 volts. Thus, a 66,000-volt insulator would have a leakage length of about 53 inches from wire to pin.

Insulator Pins.—Insulator pins for high-tension insulators are, universally, of iron. The general form most used for mounting on crossarms is shown in Fig. 96. This pin is made up of a stud varying from ¾ to ⅞ in. in diameter, threaded at both ends. This stud passes through a hollow, cast- or malleable-iron stand which is threaded at the top, and the upper end of the stud screws into these threads. The lower end of the stud passes through the hole in the crossarm, and the pin is fastened tightly to the crossarm by screwing up the bottom nut against the under side of the crossarm, the bottom of the stand pressing against the upper surface of the crossarm. The upper end of the stud projects above the end of the supporting stand, and on to the threads of this exposed portion the thimble is fastened. Customarily, the thimbles are cemented into the insulators at the

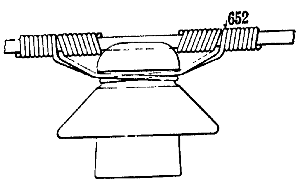
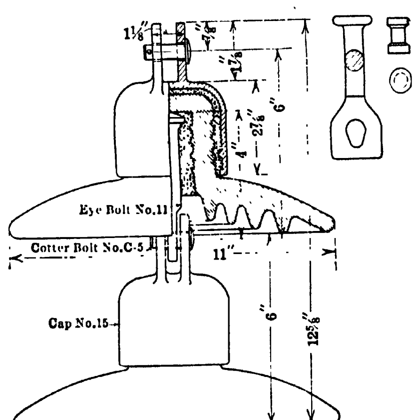


Fig. 99.—Method of tying to insulator.



R. Thomas & Sons Co.

Fig. 100.—Suspension insulator.

factory, and the insulator, therefore, is screwed into place, the screw threads being in metal, both on the pin and in the thimble. The stand forms not only a spacer to fix the height of the pin above the crossarm, but acts also as brace to take horizontal stresses applied at the upper end of the pin.

There are other forms of insulator pins, but the best for economical erection is one which can be fastened tightly to the crossarm without the insulator thimble being in place. Pins can be put in place on the crossarms before the poles are set, and the insulators afterward screwed on when the lineman climbs to the pole head to string the wires.

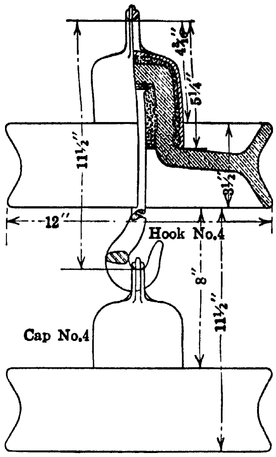


FIG. 101.—Suspension strain insulator.

Whenever insulator pins are placed on pole tops, a special form, called the pole-top pin, is used. These may be either of malleable iron or a forging of standard 2-in. pipe, wedged down and threaded at its upper end. Figs. 97 and 98 show, respectively, these two varieties of pins.

Method of Tying.—The wires have to be tied in place on each insulator and a number of methods of tying are in use. The best, however, is the double-bridle tie which is shown in Fig. 99. As indicated, two tie-wires are used no each insulator. The end of one is wrapped around the wire mak-

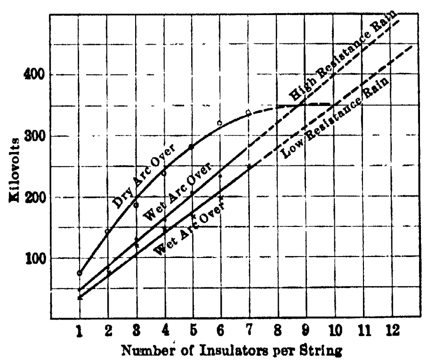


FIG. 102.—Characteristic curves of suspension insulator.

ing from eight to ten turns, beginning about 8 in. back from the center line of the insulator. The free end is then brought forward, passed around the insulator, brought back to the inner end

of the coil first made about the main wire, and securely wrapped about it, as shown. A similar bridle is put on the opposite side. These wires must be pulled up tight and wrapped firmly, as it is on them that the real strength of the line depends. Tie-wires are usually No. 4 wire and of the same metal as that of the main-line conductor. Larger tie-wires have sometimes been used though it is impractical to make a good tie with wire larger than No. 2.

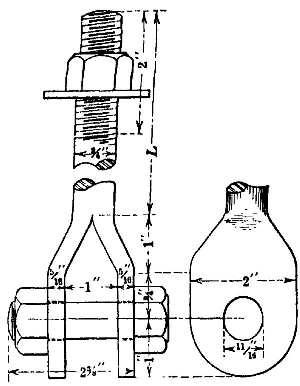


FIG. 103.—Suspension eye-bolt.

Suspension Insulators.—Suspension insulators are made of disks of porcelain, which are provided with metal fittings cemented into place, the upper one forming either a receptacle for a hook or a pin joint, the lower one forming a hook or a pin-joint eye. Figs. 100 and 101 show both kinds. The disks are connected together by the hooks, or by the pin joints, as indicated. Each disk, or insulator, can safely resist a certain voltage, and by stringing several of them together the total voltage which the string can resist can be brought up to any desired value

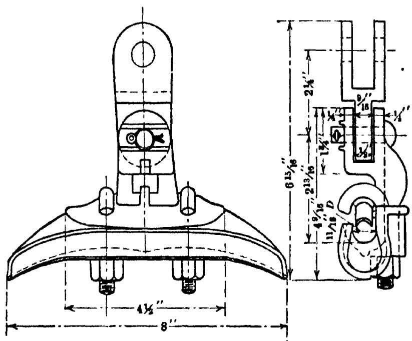


FIG. 104.—Suspension clamp.

within reasonable limits. The resisting voltage of a string is not, however, the sum of the resisting voltages of the several insulators in the group. The disk next to the line is subjected to a greater stress than the next succeeding one and the third disk has a less

stress imposed on it than the second, and so on. The potential gradient of a string of disks is very similar to that of a series of gaps between the discharge cylinders of a multi-gap lightning arrester, as shown in Fig. 176. In Fig. 102 are shown three curves which indicate the increase in voltage with increase in the number of disks per group. It is to be observed that the voltage curve for dry weather begins to fall off rapidly after the number of insulators exceeds four. The curves for wet weather are practically straight lines, showing that for this condition, the resistance increases approximately in direct proportion to the number of insulators. This latter result is, of course, due to an equalization of the electrostatic gradient over the whole group by the moisture.

These insulators are suspended from crossarms by special hardware designed for this purpose. Fig. 103 shows an eye-bolt for suspending a pin-connected group from a crossarm. The wire is fastened to the insulator by means of a suspension clamp, which latter is fastened to the hook, or eye-bolt on the insulator. Fig. 104 shows a suspension clamp of this kind.

The following table shows the approximate weights of insulator strings, for different voltages.[1]

TABLE 8

WEIGHTS OF INSULATOR STRINGS

Working voltage	Weight, lb.
20,000	3
40,000	11
60,000	23
80,000	40
100,000	60
120,000	80
140,000	100

Creighton gives the following as the desirable qualities which any insulator should possess.[2]

1. It shall be mechanically strong in compression and tension.
2. It shall be tough, not brittle or fragile.
3. It shall be non-porous.

[1] Overhead Electric Power Transmission, by Alfred Still. McGraw-Hill Book Co.

[2] *Trans.* A. I. E. E., February, 1915.

4. The porcelain shall be without appreciable cracks, laminations, cavities, conducting flaws, or air pockets.

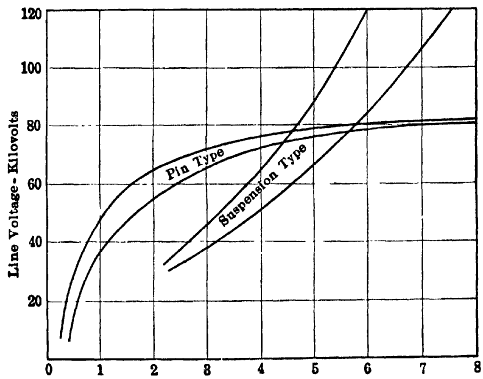
5. It shall be of a fair, uniform dielectric strength.

6. It shall have a permanent glaze without cracks, roughness or checks to hold dirt in the surface. It is desirable to have the glaze as non-hygroscopic as it is possible to obtain without sacrificing other factors.

7. Incidentally, the coefficient of expansion of the porcelain should be low in order to permit of sudden changes of temperature due to the weather conditions.

8. The parts should be held together with non-changeable cement.

9. In the matter of design the general rule to follow should be to keep the distance between the metal electrodes as great as the me-



Locke Insulator Co. 1914–1915.

FIG. 105.—Cost of insulators.

chanical strength will permit. In general, this rule calls for thicker porcelain than can be economically manufactured.

10. The design should be such that the air around the insulator is weaker to puncture than the thickness of the porcelain even under super-spark potentials.

11. The design should be such as to give a relatively long drip space for water so as to hold a high value of spark-over potential during a rain.

12. For dusty countries extra lengths of creepage surface should be provided.

It is far easier to state what is desired than it is to make definite recommendations of how the desiderata are to be obtained. Every possible avenue of investigation should be tried until the desired perfection of insulator is reached.

Comparative Costs of Insulators.—Fig. 105 is a diagram showing the range of costs of insulators of various kinds during 1913 and 1914, as given by the Lock Insulator Co. While the prices fluctuate considerably, the cost of any insulator will be somewhere between the maximum and minimum curves shown.

Following are the specifications for testing insulators as fixed by the A. I. E. E.

1. (*a*) This specification is intended to cover the checking of the design and the testing and the inspection of the factory output, of ....porcelain insulators, cat. No..........of............... Company; to be manufactured for the ....Company.

(*b*) The operating voltage is...............and the frequency is................

(*c*) Definitions: By "insulator" is meant the complete insulator or group of insulating members including all the parts necessary to support the conductor from the crossarm, or on the pin, as the case may be.

By "unit," or "unit insulator," is meant a suspension insulator element complete, having a metal cap and pin.

By "shell" is meant a single porcelain piece without cement or cap or pin.

2. Drawings.—A dimensioned drawing shall be furnished, showing the complete insulator and metal parts, or, if the insulators are built up or composed of a string of units, showing the details of a unit and all the clearances between units and hardware.

3. Inspection.—The maker will give to the purchaser or his representative such access to his works at all times during working hours as is reasonable and necessary to determine the suitability of material to be supplied, and shall furnish all necessary apparatus, labor, and other facilities for making the tests herein called for, without cost to the purchaser. All good insulator units destroyed in the tests here called for are to be paid for by the purchaser at the contract price.

All insulators are subject to final inspection, test and acceptance at maker's factory.

Neither the inspection, nor waiving of inspection, nor the purchaser's acceptance, will relieve the maker from obligation to furnish material in accordance with this specification.

4. Design.—All insulators shall be designed, as far as may be practicable, to fail by flashover, and not by puncture, under excess voltage tests, especially under impact tests.

Insulators shall be of robust construction and design so as not to be easily injured in handling.

Explanatory Note.—The ultimate criterion of the merit of an insulator is its performance in service, and the best available measure thereof is

its behavior under definite tests. However, as no practicable tests actually reproduce service conditions, for example in the matter of high-frequency voltage or deposits of dust, criticism on theoretical grounds is valuable, and, other things being equal, preference should be given to the insulators most closely conforming to theoretically best designs.

NOTE.—Careful attention in specifying flashover voltages should be given to the fact that for varying altitudes the breakdown strength of air varies approximately, though not exactly, as the barometric pressure.

METAL PARTS

5. Corrosion.—All metal parts shall be of non-corrodable material or shall be galvanized, or sherardized, in accordance with the specifications for galvanizing prescribed by the joint committee of the National Electric Light Association in its Specification for Overhead Crossings of Power Lines above Telephone and Other Low-voltage Lines. Surfaces shall be free from roughness or projecting points; bearing surfaces shall be smooth enough not to injure cables.

6. Factor of Safety.—Metal parts shall have a factor of safety of at least three over the maximum stress that they receive in service, except that with pins for pin-type insulators, the factor may be reduced to two where a higher factor is impracticable. The maximum service strain is here agreed upon as........lb.

PORCELAIN

7. Quality.—All porcelain shall be dense and homogeneous, as is best adapted to high-tension insulator requirements, free from injurious cracks, blisters and flaws, or other defects that would render them unfit for use in insulators. The burning of all porcelain sections shall be done so as to insure even vitrification but shall not render the porcelain unduly brittle. The surface shall be smooth and uniform and the body of the porcelain shall be moisture-proof.

8. Glazing.—The glazing shall be of..........color and of a reasonably uniform shade, smooth, hard and continuous over all surfaces except those to be in contact with the cement. It shall be unaffected by weather, ozone, nitric acid, nitric oxides, alkali dust, or sudden change in temperature over the atmosphere range.

9. Absorption—Explanatory Note.—While imperviousness of the porcelain to moisture is of supreme importance, no satisfactory test of this quality is known.

CEMENT

10. Assembling.—All cemented joints between insulator parts shall be carefully made, using for this purpose the best grade of neat Portland

cement, thoroughly mixed, and plentifully supplied with moisture during setting. The assembly shall be so done that no hollows, or voids, will be left between the cemented surfaces. All superfluous cement must be cleaned off of the insulator before crating.

Electrical Testing.—NOTE.—Sections 11 to 15 inclusive are particularly applicable to competitive tests and to tests the results of which are to be compared to similar tests made with other testing apparatus. In cases where merely a comparative study of different designs of the same make is to be made, all tests being carried out on the same testing apparatus, it is usually satisfactory to use the standard test apparatus of a first-class maker.

It should be definitely stated in the contract whether §§11–15, inclusive, are to be adhered to or not.

11. Wave Form.—The wave form of the generator shall be a true sine curve within the limits specified for generators by the Standardization Rules of the American Institute of Electrical Engineers and may be checked by the methods therein prescribed.

12. Control of Voltage.—The voltage shall be controlled in such a way as not to distort the wave form. (One satisfactory method of control is the use of a regulator consisting of a shunt resistance connected directly across the low-voltage side of the transformer, and a series resistance in the supply. The shunt resistance must always by-pass at least five (5) times the exciting current of the transformer. The principal control is effected by the series resistance. This method is often spoken of as the potentiometer method.)

13. Measurement of Voltage.—The method of measuring the voltage on the test circuit shall be that recommended by the American Institute of Electric Engineers, covering such cases.

14. Kilovolt-ampere Capacity of Testing Apparatus.—The kilovolt-ampere capacity of the testing apparatus, including any series resistance used, is important, for the leading current taken by the insulators tends to alter the voltage of the test apparatus. The maximum current taken from the test apparatus shall not be so great as to distort the voltage wave more than permitted for generator electromotive force waves by the A. I. E. E. Standardization Rules.

15. Surrounding Conditions During Tests.—In *design checking* tests of insulators having an operating voltage not exceeding 75,000 volts, no object, other than leads and supports should approach nearer than 6 ft. (1.8 m.) to the insulator. For insulators having a higher operating voltage, the conditions for the "design test" of complete insulators should be made, as nearly as practicable, the same as the conditions of actual service as regards the grounding of one side of the insulator and the arrangement and distance of grounded objects in the neighborhood. A conductor of 6 ft. (1.8 m.), or more, in length, extending

equally on both sides of the clamp, should be used to represent the transmission wire.

NOTE.—In these tests the walls of the room will ordinarily introduce a very serious departure from the conditions of outdoor service. Open-air tests, where feasible, are preferable from this point of view.

Routine tests, not being on complete insulators or insulator strings, do not require these precautions.

16. Frequency.—Tests should be made at the frequency at which the insulator is to be used. Where special agreement is made, tests may be made at 60 cycles on insulators intended for use on higher and lower frequencies. No error of a serious magnitude will be expected within the range of 25 to 133 cycles.

17. What Constitutes a Breakdown or a Flashover.—An insulator is said to "fail," or "break down," under a voltage test whenever a puncture occurs in any part of the insulator. It is said to flash over when a discharge of any sort passes all the way from one terminal to the other, since such a discharge would be followed by an arc on a power line.

Local breakdown, either corona or local sparks, while an important symptom, indicating severe local stress, does not constitute a flash-over. The weight to be given to such local breakdown, however, is a matter of judgment.

18. Rain Tests.—Water should be sprayed on the insulator at a uniform rate averaging 1 in. (2.5 cm.) depth in 5 min., and should be reasonably uniformly distributed over the whole insulator. The rate of precipitation shall be measured by collection of water in a pan at the location of the insulator, the insulator being removed. A fairly satisfactory spray in the form of a fine mist can be obtained by some forms of spray nozzles where pressure is available.

The spray shall strike the insulator at an angle of approximately 45° with the vertical.

The water used shall have a high specific resistance, not less than 5000 ohms per cubic inch (12,7000 ohms per cubic centimeter). Pure water may often be obtained from condensed steam or melted ice, preferably artificial ice, or rain. Municipal water supplies are often so impure as to seriously impair the performance of the insulator on the wet flashover.

When insulators are to be used in localities subjected to salt spray, or alkali, or acid mists, or to conditions producing dew deposits, special tests may be agreed upon.

19. Puncture under Oil.—Tests on a certain percentage of insulator units, ordinarily not exceeding ¼ per cent., should be made to determine the ability of the insulator to resist puncture and to measure the uniformity of the product. This test is best made by submerging the insulator in oil.

For this test each suspension insulator unit should be completely assembled with its standard hardware.

With pin-type insulators, there should be attached to the head of the insulator wires representing the tie and line wires, and a metal pin should be placed in proper manner in the pin hole.

The test voltage should then be applied to the hardware in each case. The puncture value obtained under these conditions should not be less than 135 per cent. of the dry flashover voltage and should where possible, be much higher. In the case of suspension units, a factor approaching 200 per cent. has sometimes been obtained.

The puncture voltage that must be met in the actual tests (§24) should be here specified for each contract, viz....volts.

In making the test, apply to the insulator a voltage 30 to 40 per cent. below the dry flashover value and then raise the voltage gradually, or by steps, until puncture occurs, at a rate of about 5000 volts per second. The puncture value of the porcelain is very sensitive to the length of time voltage near the maximum is applied; the puncture voltage may be lowered as much as 20 per cent. by long-continued application of the test voltage. It is well to have a short air gap between each insulator under test and the testing line, that the character of the charging current may be judged by the appearance of the arc.

Pin-type Insulators

20. Inspection.—All parts shall be inspected before assembling.

21. Routine Tests—Electrical Tests before Assembling.—All insulator shells, before being assembled, shall be tested for 3 min. at the voltages given in the following table. Should any shell be punctured in the last minute of test, the test will then be continued, after the removal of the punctured piece, until no puncture occurs in one full minute of test. These tests are to be conducted by inverting the parts in pans of water and placing water inside the several pieces, the potential then being applied to the two bodies of water.

Note.—The water both inside and outside shall be filled to within ¼ in. of the highest point to which the later applied, conducting parts, including cement, will extend.

The individual tests in the various shells shall be as follows:

Head..	volts
Second shell..............................	volts
Third shell..	volts
Fourth shell..............................	volts
Center..	volts

22. Routine Tests—Final Electrical Tests.—All completed insulators shall be tested according to one or the other of the four following tests.

One of these tests should be definitely specified for each lot of insulators tested under these specifications.

(*a*) The insulators in groups shall be subjected to a voltage steadily applied, just below the flashover voltage, for a period of 3 min. The voltage shall be held at such a point that a flash shall occur over some insulator of the set occasionally, but not more often than once in 3 sec. This test involves a steady voltage stress and gives an opportunity for the heating up to the puncture point of any spots in the porcelain which may be sufficiently defective. For this test it is, therefore, objectionable that there should be frequent flashing over, as each flashover presumably removes the potential from all insulators for one alternation.

If an insulator of the group punctures during the last minute of the test, the test shall be continued until one full minute elapses without a puncture.

(*b*) The insulators in groups shall be subjected to a voltage in excess of the flashover voltage so that a continuous succession of flashovers exists, this being continued for a period of 2 min. This test is intended to introduce the effect of impact and, consequently, continual flashover is necessary.

(*c*) The insulators in groups shall be given test (*a*) above, followed by test (*b*). The first test may be changed into the second by merely raising the potential, without removing the voltage. In this case the time of the second part of the test should be reduced to 1 min.

(*d*) This test is the same as test (*b*) above except that, instead of applying this testing to insulators in groups, the insulators shall be tested singly and the voltage continued for a period of 20 sec.

NOTE.—In all the tests (*a*), (*b*), (*c*) and (*d*) above, it is important that the current be so limited in volume that no power arc shall follow a flashover, as otherwise the voltage will be substantially removed from the insulators during the continuance of the power arc.

23. Design Test—Mechanical.—The following design test shall be made on enough complete insulators, usually not exceeding ¼ per cent., to determine the behavior of the design and the uniformity of the product.

The insulators shall be capable of withstanding for 15 sec., without signs of distress, a pull of........lb. (..........kg.) applied at the tie-wire groove in a direction at 90° with the axis of the insulator and pin. For the purpose of making this test, the insulator shall be mounted on the pin to be used in service. In case of failure, the question as to whether the insulator or the pin is at fault shall be determined by testing again with a solid steel pin turned from a piece of round steel of such dimensions that this piece of steel acting as a pin for the insulator will not bend under the above-mentioned load.

It is desirable that a number of insulators be tested to destruction to show approximately the margin in mechanical strength.

24. Design Tests—Electrical.—The following design tests shall be made in enough complete insulators to determine the performance of the type. The insulator shall stand without failure:

(*a*) A test for *flashover, dry*, of three times the potential between line wires, applied for 1 min.

(*b*) A test for *flashover, wet*, of not less than two times the potential between line wires, applied for 1 min.

(*c*) Puncture test under oil shall be made as specified under §19 above.

Suspension-type Insulators

25. Routine Tests—Electrical Test before Assembling.—All insulator shells shall be tested according to one or the other of the three following tests. One of these tests should be definitely specified for each lot of shells tested under this specification.

(*a*) The shells in groups shall be subjected to a voltage steadily applied, just below the flashover test for a period of 3 min. The voltage shall be held at such a point that a flash shall occur over some shell of the set occasionally, but not more often than once in 3 sec. This test involves a steady voltage stress and gives an opportunity for the heating up to the puncture point of any spots in the porcelain which may be sufficiently defective. For this test it is, therefore, objectionable that there should be frequent flashing over, as each flashover, presumably, removes the potential from all insulators for one alternation.

If a shell of the group punctures during the last minute of the test, the test shall be continued until one full minute elapses without a puncture.

(*b*) The shells in groups shall be subjected to a voltage in excess of the flashover voltage so that a continuous succession of flashes exists, this being continued for a period of 2 min. This test is intended to introduce the effect of impact and, consequently, continual flashover is necessary.

(*c*) The shells in groups shall be given test (*a*) above, followed by test (*b*). The first test may be changed into the second by merely raising the potential at the end of the first test. In this case, the time of the second part of the test should be reduced to 1 min.

Note 1.—In all the tests (*a*), (*b*) and (*c*) above, it is important that the current be so limited in volume that no power arc shall follow a flashover, as otherwise the voltage will be substantially removed from the shells during the continuance of the power arc.

Note 2.—In making these tests the insulator shells are to be inverted in a pan of water and water placed in the inside. The water both inside

and outside shall be filled to within ¼ in. of the highest point to which the later-applied conducting parts, including cement, will extend.

26. Routine Test—Mechanical Test.—After at least 10 days' setting of the cement, all units shall withstand for 3 sec., without signs of distress, a mechanical pull of .... lb. (........ kg.), in line with the axis of the insulator. Insulators may be given this test after a shorter period of setting, at the risk of the maker.

27. Routine Test—Final Electrical Test.—All completed insulator units shall be tested according to one or the other of the four following tests. One of these tests should be definitely specified for each lot of insulators tested under this specification.

(*a*) The insulator units in groups shall be subjected to a voltage steadily applied, just below the flashover test, for a period of 3 min. The voltage shall be held at such a point that a flash shall occur over some unit of the set occasionally but not more often than once in 3 sec. This test involves a steady voltage stress and gives an opportunity for the heating up to the puncture point of any spots in the porcelain which may be sufficiently defective. For this test it is, therefore, objectionable that there should be frequent flashing over, as each flashover, presumably, removes the potential from all units for one alternation.

If a unit of the group punctures during the last minute of the test, the test shall be continued until one full minute elapses without a puncture.

(*b*) The insulator units in groups shall be subjected to a voltage in excess of the flashover voltage so that a continuous succession of flashes exists, this being continued for a period of 2 min. This test is intended to introduce the effect of impact and, consequently, continual flashover is necessary.

(*c*) The insulators in groups shall be given test (*a*) above, followed by test (*b*). The first test may be changed into the second by merely raising the potential at the end of the first test. In this case, the time of the second part of the test should be decreased to 1 min.

(*d*) This test is the same as test (*b*) above, except that instead of applying this testing to units in groups, the units shall be tested singly and the voltage discharges continued for a period of 20 sec.

NOTE.—In all the tests (*a*), (*b*), (*c*) and (*d*) above, it is important that the current be so limited in volume that no power arc shall follow a flashover, as otherwise the voltage will be substantially removed from the insulators during the continuance of the power arc.

This test shall be made after the mechanical test above prescribed, §26.

29. Design Tests—Electrical.—The following design tests shall be made on enough complete assembled insulators, not exceeding ½ per cent. to determine the performance of the type.

(a) A test for *flashover, dry*, of one insulator unit having its normal position in the string, and of a complete insulator string consisting of .... units, of .... volts, and .... volts respectively, applied for 1 min.

(b) A test for *flashover, wet*, of a single insulator and of the string, of...... volts and...... volts respectively, applied for 1 min.

(c) The puncture test under oil shall be made as specified under §19 above.

It is preferable that the arc-over of the complete insulator, when the test voltage is sufficiently raised, shall be over the insulator as a whole and shall not be over the individual elements.

30. Design Tests—Mechanical.—The following design test shall be made on enough complete insulators, usually not exceeding ¼ per cent., to determine the behavior of the design and the uniformity of the product.

After at least 2 weeks' setting of the cement, the insulators to be tested shall withstand for 15 sec. without signs of distress a pull of...... lb. (....... kg.) in line with the axis of the insulator.

It is desirable that a number of these insulators be pulled to destruction to show approximately the margin in mechanical strength.

APPENDIX

The following tests are recommended as desirable where appropriate. They are not incorporated in the above specifications, as experience with them is not yet sufficiently broad.

31. Uniformity Puncture Test.—Twenty-two single insulators, chosen at random from stock, which have passed all routine tests, shall each in turn be punctured under oil, as provided for oil tests in §19 above. Any 20 of these values of puncture voltage shall then be selected by the maker. The difference between the maximum and minimum of these 20 puncture voltages must not be more than 20 per cent. of the average voltage. This test should be repeated with one or more additional groups of 22 disks, not exceeding in the aggregate ¼ per cent. of the total, enough to determine the uniformity of the product. In case of failure of the lot to pass this test, the other insulators from the same burnings shall be tested, as specified under §28, but for a period five times that there specified.

32. Design Test—Impulse Test.[1]—Ten units shall be selected at random. Each of these disks shall be connected in turn to the impulse circuit shown in Fig. 106. The gap A shall be set at three or, preferably, four times the arc-over voltage of a single unit. The voltage shall be

[1] For an example of the application of such a test see paper by IMLAY and THOMAS, *Trans.* A. I. E. E., vol. XXX, 1912.

increased until gap *A* sparks over, when the circuit shall be immediately opened by breaker, or the voltage otherwise removed. This shall comprise a "stroke." Such strokes shall be repeated on each unit or string of units up to...... strokes, or until puncture occurs. Preference shall be given to the design or make of insulator showing the greatest uniformity and the highest resistance to puncture. Referring to Fig. 106, the shunt-condenser capacity shall be equal to that of an air-plate condenser having from 75 to 100 sq. ft. surface on each plate and a spacing equal to 25 per cent. more than the sparking distance of the voltage used. The connections from the condenser to the insulator should be as short as practicable.

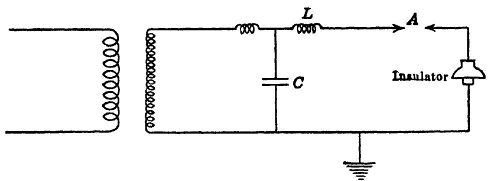


FIG. 106.—Connections for impulse test.

NOTE.—The above test will show, in a general way, the probable effect of surges, lightning, etc., on the life of the insulator, as well as the uniformity of the porcelain. While there is not sufficient experience with this test to secure a numerical measure of the number and sort of strokes that must be withstood by the insulator to insure a puncture-proof product, the test as outlined above is very important in competitive tests.

33. Design Test—Combined Mechanical and Electrical Test.—The following design test should be made upon enough insulators to determine the performance of the design and the uniformity of the product.

An insulator placed in an insulated testing machine and impressed with a voltage just under or just over the flashover voltage (as may be agreed upon) shall be subjected to a gradually increasing mechanical pull until puncture occurs.

The insulator should not puncture at less than twice, or, preferably, three times the maximum pull to which the insulator is to be subjected in service, as fixed in §6 above.

34. Uniformity—Brittleness Test, Applicable Especially to Suspension Insulators.—The following uniformity test should be made upon enough insulator units to determine the performance of the design and the uniformity of the product.

A completed insulator unit which has passed all routine tests shall be placed in ice water, and the temperature of the water raised to boiling. The heating should not begin until after the insulator has been in ice

water 15 min. to permit all parts to come to the same temperatures. The water should then be heated at a uniform rate of about 1°C. per minute. After remaining at boiling temperature for 30 min., the unit may be removed and should afterward be tested either by the measurement of its insulation resistance, using 1000 or 2000 volts for the measurements, or by the standard routine electrical test (§28), or both.

35. Percentage of Failure in Routine Tests.—The percentage of punctures in the electrical tests is a rough measure of the burning of the porcelain and the care in manufacture. A relatively large percentage of failures, perhaps over 5 per cent., suggests under-firing. It is recommended that the following modification be applied to routine tests §22 and §28:

"When the percentage of punctures in any group of insulator units, or shells, under test simultaneously, exceeds 5 per cent., the length of the time of application of the test voltage shall be doubled for that group."

CHAPTER VIII

POLE AND TOWER LINES

Right-of-way.—Carrying a transmission line across country involves the necessity of purchasing the right from property owners to plant poles or erect towers, string wires, and, at all times, have free access to the line. In some cases, it has been necessary to purchase a strip of land for this purpose, just as a railway, occupying the land, would be obliged to do. Usually, however, it is only necessary to pay for pole, or tower, rights. Sometimes this takes the form of a flat payment for the right in perpetuity, and in other cases, a yearly rental is exacted.

The way must be cleared of all trees tall enough to fall against the line in case any one of them should be broken off or uprooted by storms. Lines supported on tall towers do not require so much wood cutting as lines on shorter poles. The cost of tree felling is not, really, a permanent disbursement, as the timber or firewood obtained usually sells for more than the cost of labor.

While as direct a route as possible should be chosen for the line, it does not pay to place it far from a railway or good country road, and even if the line has to diverge considerably from its natural direction, an accessible route should be chosen. The distributing of poles, or towers, reels of wire, tools and fittings, and the necessity of patrolling the line after it has been built, make it necessary to have it adjacent to a highway, except under unusual conditions which justify diverging from the road.

Pole and Tower Lines.—Transmission lines are supported by poles or towers. The poles may be of wood, steel latticework, tubular iron, or reinforced concrete. Steel towers are simply lattice poles greatly increased in their dimensions. It is customary to use steel towers for lines on which the pressures exceed 66,000 volts. The reasons given for the use of towers are that they are durable, permanent structures, and their adoption is necessary because of the great crossarm lengths required for suspension insulators. Also it is cheaper to use towers and place

them at considerable distances apart than to use small structures and place them closer together. In the opinion of the author, there are very few conditions which justify the use of steel towers, and a large percentage of the steel-tower lines, now in use, have required an investment and consequent interest and depreciation charges, both of which are greatly in excess of the corresponding costs of a well-constructed, pole-supported line. This subject will be discussed later in more definite detail.

In the adoption of any form of support, its strength must be sufficient to resist the following stresses:

(*a*) Vertical forces due to weight of structure and wires.

(*b*) A bending or overturning moment due to wind pressure against surface of supporting structure plus one-half the length of each wire between adjacent spans attached to the support. This force acts at right angles to the direction of the line.

(*c*) The unbalanced longitudinal force set up by the accidental breaking or burning loose of a certain proportion of the wires carried by the supporting structure. This proportion is usually taken as one-third the total number of wires carried by the support though some engineers have considered that two-thirds the total number of wires may be broken or burned and have designed supports on this basis.

(*d*) The twisting moment produced by the breakage of one or more wires.

The bending moment at the ground line due to the side pressure of the wind, is equal to $M_1 + M_2$.

M_1 = moment produced by wind pressure against the pole and
M_2 = moment produced by wind pressure against the wires.

$$M_1 = \frac{P_1 H_1 (D_1 + 2D_2)}{72} \text{ lb.-ft.} \qquad (34)$$

P_1 = wind pressure per square foot of projected area of pole, usually taken at 15 lb. per square foot.
H_1 = height of pole above ground, in feet.
D_1 = diameter of pole at ground line, in inches.
D_2 = diameter of pole at top line, in inches.

$$M_2 = \frac{P_2 H_2 nd (S_1 + S_2)}{24} \text{ lb.-ft.} \qquad (35)$$

P_2 = wind pressure against wires, in pounds per square foot of projected area, usually taken as 10 lb. per square foot.
H_2 = height of wire above ground, *in feet.*

n = number of wires.
d = diameter of wire, *in inches.*
S_1 and S_2 are lengths of spans adjacent to pole, in feet; usually, $S_1 = S_2$

The moment of resistance to flexure of a round pole is

$$M_r = \frac{f\pi D^3}{384} = \frac{fD^3}{122} \tag{36}$$

f = maximum stress at outer fibre, per square inch.
D = diameter of pole in inches, at point for which M_r is computed.

The deflection of a round pole is

$$\delta = \frac{PL^3}{3EI} \tag{37}$$

For a wood pole having a modulus of elasticity of 1,500,000, this becomes

$$\delta = \frac{ML^2}{22 \times 10^4 \times D^4}$$

δ = deflection in feet.
M = bending moment in lb.-ft. $= PL$
P = total pressure against pole to deflect it.
L = height from point about which moment is taken (usually ground line), to point of application of P, in feet.
E = modulus of elasticity of material = 1,500,000, average for timber.
I = moment of inertia $= 0.0491D^4$ for a circular section and $0.0833b^4$ for a rectangular section in which D = diameter, and b = length of side of the square, in feet.

The ultimate strength of various pole timbers is given in the following table.

Table 9.—Strengths of Various Pole Timbers, in Flexure
(Fiber Stresses at Rupture)

Cedar	3500 to 5600 lb. per square inch.
Chestnut	4500 to 9700 lb. per square inch.
Cypress	6000 to 7000 lb. per square inch.
Long-leaf pine	8000 to 8600 lb. per square inch.
Short-leaf pine	7000 to 7700 lb. per square inch.

Griswold[1] has made a number of tests on pole timbers, from which he has plotted a series of curves shown in Fig. 107. These

[1] *Trans.* A. I. E. E., April, 1912.

curves show the total bending moments at which the different kinds of poles, and having various diameters, broke. This diagram can be used in the selection of a pole for a given applied stress. If the bending moment on the pole be multiplied by the desired factor of safety, the product is the value to be taken

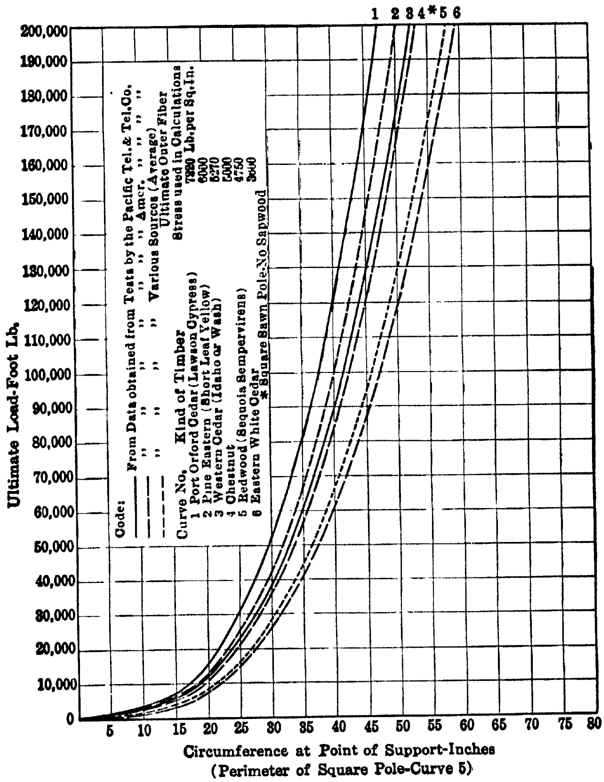


FIG. 107.—Strength of pole timbers.

on the line of "ultimate load," in foot-pounds, and the ordinate of the particular curve selected will give the circumference of the pole required to resist the given bending moment and have the factor of safety adopted.

As an example, assume a chestnut pole 40 ft. high above the ground line, and having a maximum force of 2000 lb. acting

against it at the top. What is the size of pole required to resist this force, with a factor of safety of $2\frac{1}{2}$?

Bending moment at the ground line $= 40 \times 2000 = 80{,}000$. Bending moment, multiplied by factor of safety $= 2\frac{1}{2} \times 80{,}000 = 200{,}000$.

The abscissa corresponding to the ordinate 200,000 on curve No. 4 for chestnut poles is 53, which is the required circumference of the pole at the ground line.

The weakest point of a pole, acting as a cantilever with the force applied at its small end, is where $d_1 = 1.5d$, d being the top diameter and d_1 the diameter at the weakest point. This fact is deduced as follows:[1]

Bending moment of cantilever is Px lb.-in. in which x is the distance from the end at which the force is applied to the section where the bending moment is to be taken, and P is the force applied.

If the stress T, in the outermost fibres is expressed in pounds per square inch, and the section is assumed circular:

$$Px = \frac{T\pi d^3}{32}.$$

The diameter at any point x in. below the section of diameter d, is $d + tx$, t being taper of the pole, or the increase in diameter per inch length. Hence,

$$T = \frac{32P}{\pi} \times \frac{x}{(d + tx)^3}.$$

In order to find the position of the cross-section at which the pole is most likely to break—that is to say, where the fibre stress is a maximum—it is necessary to differentiate the last equation with respect to x and find the value of x which makes this differential equal to zero. This gives

$$x = \frac{d}{2t}$$

for the point where the stress T is a maximum. The position of this cross-section is, evidently, not necessarily at ground level. If this value of x equals or is greater than H, then the maximum fibre stress will be at ground level, and it is calculated by substituting H for x in the formula, H being the height of the pole in inches.

[1] Overhead Electric Transmission, by Alfred Still. McGraw-Hill Book Co.

The diameter of the pole at the weakest point is:

$$d_\omega = d + tx = d + t\left(\frac{d}{2t}\right) = 1.5d.$$

and it is only when the diameter at ground level is greater than one and a half times the diameter where the pull is applied that the pole may be expected to break above ground level.

If the stress T, the taper t, and the pole-top diameter d, are known, the allowable load P is readily calculated as follows:

$$\text{Bending moment} = Px$$

$$\text{Resisting moment} = \frac{\pi d^3_\omega}{32} \times T.$$

But

$$x = \frac{d}{2t} \text{ and } d_\omega = 1.5d.$$

Substituting these values and equating the bending and resisting moments

$$\frac{Pd}{2t} = \frac{T\pi(1.5d)^3}{32}$$

whence

$$P = 0.662Ttd^2.$$

Similarly, if the pull P is known, the pole-top diameter should be:

$$d = \sqrt{\frac{P}{0.662Tt}}.$$

The woods which are suitable for poles and generally used are: white Michigan cedar, chestnut, Western yellow pine, Southern yellow pine, and red cedar. Other woods are occasionally used, particularly when the transmission line is built in sections where some certain growth is locally abundant and easily obtained. Juniper, cypress, locust and catalpa are among these latter varieties.

The wood should be cut from well-grown trees and when the sap is down, usually, between October and April. If practicable, it should be thoroughly air-seasoned. Where the poles are required in a short time, water-seasoning is resorted to. This consists of soaking the poles in a stream from 30 to 40 days and subsequently air-drying for at least 35 days of dry weather, the total time of air-drying being 35 days plus all additional days of damp or wet weather occurring during the period. In some cases,

the poles have been kiln-dried, but this usually adds considerably to the expense and is avoided when possible.

The life of the poles is dependent on the character of the wood, the locality, and whether, or not, they were seasoned before planting and also dependent on the character of preservative treatment, if any. It has been found that any preservative coating, applied to green timber, actually shortens the life of the pole. The average life of poles is from 10 to 12 years. In some cases, poles have lasted not more than 8 years and, in others, particularly in the dry portions of the Southwest, they have given service as long as 25 years. In estimating depreciation, it is customary to assume the life of a pole as 10 years, giving a 10 per cent. depreciation.

There are many processes of treatment for increasing the life of poles but the one which is principally used is a surface treatment of the butt only, by painting with hot tar or a dead oil of coal tar. A better method of applying is to dip the ends of the poles in a deep tank of hot tar or creosote. This, of course, has to be done in the pole yards by the use of a derrick with which the poles can be lifted. The pole tops are usually cut wedge-shaped at an angle of about 45°. The tops should be coated with a heavy coat of white lead or tar. The gains made in the poles for crossarms should also be covered with a generous coating of white lead.

Following is a general specification for poles.[1]

GENERAL SPECIFICATIONS FOR POLES

To determine the character of poles to be used, pole lines may be divided into the three following classes:

Class "A": for heavy transmission lines or heavy distribution lines.

Class "B": for light transmission lines or ordinary distribution lines.

Class "C": for very light distribution or light secondary lines.

The purchasing company is to have the right to make such inspection of the poles as it may desire. The inspector of the purchasing company shall have the power to reject any pole which is defective in any respect. Inspection, however, shall not relieve the manufacturer from furnishing perfect poles.

[1] Locke Insulator Co.

Any imperfect poles which may be discovered before their final acceptance shall be replaced immediately upon the requirement of the purchasing company, notwithstanding that the defects may have been overlooked by the inspector. If the requirements of these specifications are not fulfilled when the poles are offered for final acceptance, not only shall the purchasing company have the right to reject the poles, but the expense of inspection of such defective poles shall be borne by the manufacturer.

All poles shall be subject to inspection by the purchasing company, either in the woods, where the trees are felled, or at any point of shipment or destination. Any pole failing to meet all the requirements of these specifications may be rejected.

All poles shall be of the best quality live timber, squared at both ends, reasonably straight, well proportioned from butt to top, peeled and with knots trimmed close.

Sizes

The circumference at the top must be not less than the following:

Poles class A...................... 20 in.
Poles class B...................... 22 in.
Poles class C...................... 24 in.

Circumference at a point, 6 feet from the bottom end must be not less than given in following table.[1]

Length of Pole	Circumference at 6′ above butt		
	A	B	C
35′			
40′			
45′			
50′			
55′			
60′			

Where poles are not truly round, the short diameter must not be less than 80 per cent. of the long diameter.

[1] This table fixed by character of timber specified. See Tables 11, 12, 13, and 14.

Quality of Timber

Dead Poles.—The wood of a dead pole is grayish in color. The presence of a black line on the edge of the sapwood (as seen on the butt) also shows that the pole is dead. No dead poles, and no poles having dead streaks covering more than one-quarter of their surface shall be accepted under these specifications. Poles having dead streaks covering less than one-quarter of their surface shall have a circumference greater than otherwise required. The increase in the circumference shall be sufficient to afford a cross-sectional area of sound wood equivalent to that of sound poles of the same class.

Fire-killed or River Poles.—No dark red or copper-colored poles, which when scraped do not show good live timber shall be accepted under these specifications.

Twisted, Checked or Cracked Poles.—No poles having more than one complete twist for every twenty (20) feet in length, no cracked poles containing large season checks shall be accepted under these specifications.

"Cat Faces."—No poles having "cat faces" unless they are small and perfectly sound and the poles have an increased diameter at the "cat face," and no poles having "cat faces" near the six (6) foot mark or within ten (10) feet of their tops, shall be accepted under these specifications.

Shaved Poles.—No shaved poles shall be accepted under these specifications.

Miscellaneous Defects.—No poles containing sap rot, evidence of internal rot as disclosed by a careful examination of all black knots, woodpecker holes, or plugged holes; and no poles showing evidences of having been eaten by ants, worms or grubs shall be accepted under these specifications, except that poles containing worm or grub marks below the six (6) foot mark will be accepted.

Crooked Poles.—No poles having a short crook or bend, a crook or bend in two planes or a reverse curve shall be accepted under these specifications. The amount of sweep, measured between the portion six feet from the lower end and the top of the pole, that will be acceptable under these specifications, is as follows:

35-ft. poles shall not have a sweep over 10½ in.
40-ft. poles shall not have a sweep over 12 in.
45-ft. poles shall not have a sweep over 9 in.

50-ft. poles shall not have a sweep over 10 in.
55-ft. poles shall not have a sweep over 11 in.
60-ft. poles shall not have a sweep over 12 in.

Defective Tops.—Poles having tops of the required dimensions must have sound tops. Poles having tops one (1) inch or more above the requirements in circumference may have one (1) pipe rot not more than one-half (½) inch in diameter. Poles with double tops or double hearts shall be free from rot where the two parts or hearts join.

Defective Butts.—No poles containing ring rot (rot in the form of a complete or partial ring) shall be accepted under these specifications.

Scattered rot, unless it is near the outside of the pole may be estimated as being the same as heart rot of equal area.

"Wind Shakes."—Poles with cup shakes (checks in the form of rings) which also have heart or star checks may be considered as equal to poles having hollow hearts of the average diameter of the cup shakes.

Inspection.—All poles shall be subject to inspection by the purchaser's representative, either in the woods where the trees are felled, or at any point of shipment, or destination. Each pole thus inspected shall be marked according to its length and class with a marking hammer, by the purchaser's representative. All poles failing to meet these specifications shall be rejected.

The *average rate of tapering of poles* is as follows:

Chestnut 3.8 to 4 in. change in circumference for each 10 ft. of length.

Michigan white cedar 5.2 in. change in circumference for each 10 ft. of length.

Western yellow pine 4 in. change in circumference for each 10 ft. of length.

Southern yellow pine 2.4 in. change in circumference for each 10 ft. of length.

Red cedar 3.5 in. change in circumference for each 10 ft. of length.

Pole Setting.—No strict rule can be laid down for method and depth of setting as this will vary with character of the soil and other factors. The following table, however, shows standard depths of settings for different sizes of poles.

The hole should be in every case large enough to have a 6-in. marginal space around the pole, that tamping may be done effectively. One shoveller to three tampers insures a solid setting. Soil should be heaped about the pole to allow for settling and drain.

TABLE 10.—DEPTH OF POLE SETTINGS

Length of pole	Depth in ground
25 ft. or less	5 ft.
30 ft. or less	5½ ft.
35 ft. or less	5½ ft.
40 ft. or less	6 ft.
45 ft. or less	6½ ft.
50 ft. or less	7 ft.
55 ft. or less	7½ ft.
60 ft. or less	8 ft.
65 ft. or less	8½ ft.
70 ft. or less	9 ft.
75 ft. or less	9½ ft.
80 ft. or less	10 ft.

(In solid rock set 2 ft. less)

Where poles are set in solid rock, pieces of rock, well filled, should be securely wedged around the pole.

In marshy ground some special means must be adopted to insure a stable and rigid setting. Sometimes this is obtained by digging out a hole of sufficient diameter to sink an ordinary

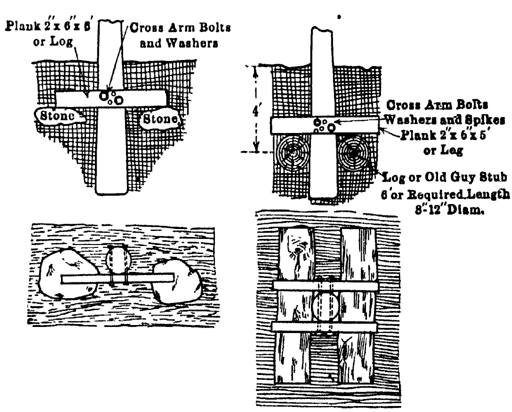


FIG. 108.—Method of setting poles in swampy earth.

barrel into it, the poles set in the center line of the barrel and the space filled in with concrete. Fig. 108 *a* and *b* give suggestions for settings that have been satisfactory in swampy territory.

Poles should be numbered after erection,, the numbers being painted in white lead and about 6 ft. from the ground line. The numbering should be consecutive from the power station to the

end of the line. All guy stubs and braces should be given the same numbers as the pole with which they are connected and designated by some letter, as *B*. A record should be made of the location of each pole and, in case of injury, necessity of removal or any other change being required, the numbers afford a simple and ready means of identification.

The following tables give the average proportions of various kinds of poles.

TABLE 11.—POLE DIMENSIONS—EASTERN AND MIDDLE WESTERN GROWTHS

Length, feet	Eastern cedar		Juniper		Chestnut	
	A circ at top = 22″ cir. 6 ft. from base, inches	*B* circ. at top = 25″ cir. 6 ft. from base, inches	*A* circ. at top = 22″ cir. 6 ft. from base, inches	*B* circ. at top = 25″ cir. 6 ft. from base, inches	*A* circ. at top = 22″ cir. 6 ft. from base, inches	*B* circ. at top = 25″ cir. 6 ft. from base, inches
25	31	34	28	33	27	30
30	34	36	33	35	30	34
35	38	38	35	40	34	37
40	42	43	40	44	37	42
45	44	47	45	48	42	46
50	48	50	47	51	46	48
55	53	55	50	53	49	50
60	57	61	56	57	51	54
65	63	66	63	63	55	58

TABLE 12.—POLE DIMENSIONS—WESTERN AND PACIFIC SLOPE CEDARS

Length of poles, feet	*A* top circ. 28 in. circ. 6 ft. from butt, inches	*B* top circ. 25 in. circ. 6 ft. from butt, inches	*C* top circ. 22 in. circ. 6 ft. from butt, inches	*D* top circ. 18½ in. circ. 6 ft. from butt, inches
20	30	28	26	24
22	32	30	27	25
25	34	31	28	26
30	37	34	30	28
35	40	36	32	30
40	43	38	34	32
45	45	40	36	34
50	47	42	38	36
55	49	44	40	38
60	52	46	41	39
65	54	48	43	

The following table gives the weights of chestnut poles and the number per carload.

These weights are approximate only, and it should be remembered that well-seasoned poles shipped in summer will weigh 10 per cent. less, and when shipped in winter and early spring will weigh about 10 per cent. more. Poles shipped green will weigh about 25 per cent. more.

Table 13.—Chestnut Poles

Length in feet	Diameter at top, inches	Approximate weight of pole, pounds	No. of poles to a carload
25	6	425	75 per single car
30	6	500	66 per single car
30	7	700	54 per single car
35	6	775	80 per double car
35	7	925	74 per double car
40	7	1230	60 per double car
45	7	1700	40 per double car
50	7	2225	24 per double car
55	7	2772	17 per double car

Corresponding data for cedar poles are as follows:

Table 14.—Cedar Poles

Length in feet	Diameter at top, inches	Approx. wt. seasoned, pounds	Approx. wt. green, pounds	No. of poles to a carload
25	6	250	325	100 to 125 single car
30	6	350	425	80 to 100 single car
30	7	450	500	70 to 80 single car
35	6	500	600	60 to 75 single car
35	7	600	750	55 to 70 single car
40	7	850	1000	60 to 75 double car
45	7	1000	1150	50 to 60 double car
50	7	1250	1400	43 to 50 double car
50	8	1450	1625	38 to 43 double car
55	7	1550	1775	34 to 38 double car
55	8	1800	2060	30 to 34 double car
60	7	2000	2300	27 to 30 double car
60	8	2500	2800	24 to 27 double car
65	7	2700	3000	21 to 24 double car
65	8	3200	3600	18 to 21 double car

Guying Poles.—Instead of subjecting poles to simple cantilever stresses, it is customary to reduce the stresses in them by guying with steel cables. Guy wires are attached to the poles near the tops and carried to some convenient point of anchorage. Obviously, a comparatively small guy wire, stressed but moderately, will greatly reduce the pole stresses, because the guy wire simply resists the force acting at the top of the pole, and has little or no moment acting against it.

The several methods of guying are shown in Fig. 109.

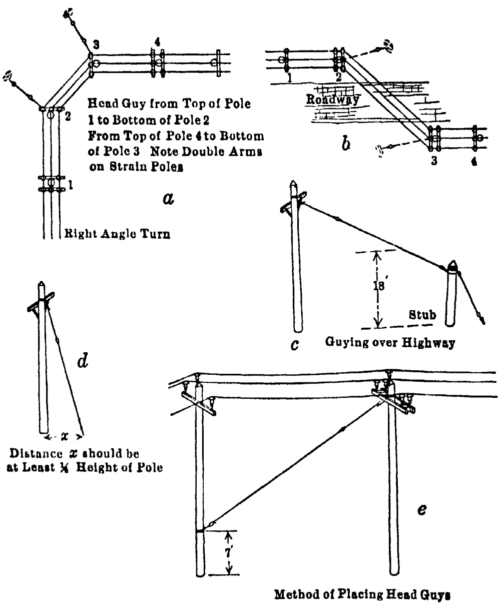


FIG. 109.—Methods of guying poles.

Head guys are anchored to the next adjacent pole. Side guys and angle guys must have anchorages prepared for them.

A cheap and effective anchor is the screw anchor. This is an iron rod 4 to 6 ft. long and having a flange at one end, which flange is not in one plane, but cut through radially and the two ends displaced axially, so that it forms a single, very wide screw thread. Where boulders are not encountered, this is screwed into the earth at an angle to the vertical so that the rod has approximately the same direction as the guy wire. An eye in

the upper end of the bar serves to twist it into the ground by passing a lever through it, and then is used for attaching the guy wires to it.

Buried logs or stones with iron rods attached are also used. Fig. 110 *a* and *b* show the arrangement and proportions of guy anchors of this latter variety.

Guy wires are made of stranded, galvanized-steel cable. The usual sizes are 3/8 in. and 1/2 in. in diameter. The cable has an elastic limit of about 100,000 lb. per square inch and an ultimate breaking strength of 200,000 lb. per square inch. The 3/8-in. cable is used for stresses under 1000 lb. and the 1/2-in. for stresses of from 1000 to 3000 lb. The 3/8-in. weighs 0.3 lb. per foot and the 1/2-in., 0.51 lb. per foot.

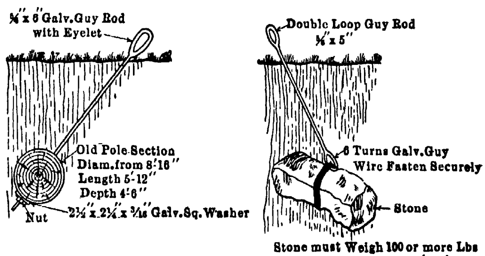


FIG. 110.—Log and stone anchors.

Guy wires are fastened to poles by making two or three turns about the pole, bringing the free end against the cable and clamping them together with a galvanized clamp.

It is customary to use side guys only when the direction of the line changes, and to take up the unbalanced pull of the wires. Good practice requires that every fifth pole be head guyed in both directions, so that in case of a transmission wire breaking, the pole line will not be pulled over, but the unbalanced pull of the remaining wires will be transmitted to the nearest head-guyed pole, where the guy wires will receive and resist the stresses produced.

Crossarms.—Crossarms are made of yellow pine or Oregon fir. Other timbers are occasionally used but these two are standard.

Certain failures of wood-pole transmission lines may be attributed to having the crossarms too light. There is no saving in initial cost by adopting small crossarms. The dimensions should be such that the maximum unit stresses in them will equal

those in the pole when the crossarm section is reduced by 33 per cent. from decay, and the pole butt reduced 10 per cent.

For a line having poles spaced 203 ft. apart and carrying one circuit of three No. 2 wires—copper or aluminium—the crossarms should not be less than 5 by 6 in. in cross-section. This assumes a total length of 7 ft., and a distance between the two wires on the crossarm of 6 ft., each wire being about 30 in. from the pole.

Specifications for crossarms should require that at least 80 per cent. be of heart timber and no single crossarm may have more than 20 per cent. of sapwood. Knots having a diameter exceeding ½ in. are objectionable. The best timber only should be used for crossarms.

Transmission-line arms have customarily five holes in them, as follows: 1-in. holes near each end, vertically through the timber, for the stud of the insulator pin. This should be at least 4 in. from the end and, preferably, 6 in., so that the tendency of the forces acting on the pin to split the arm may be resisted.

Two holes, each 7/16 in. in diameter, are drilled, one on each side of the middle line, and from 20 to 24 in. distant from it. These pass, horizontally, through the timber and at right angles to the pin holes. Into these holes the ⅝-in. lag screws, which fasten the braces to the arm, are screwed.

The fifth hole is in the middle of the length of the arm but one-third the width above the bottom edge. This hole is horizontal, 1 in. in diameter and receives the ⅞-in. through bolt which fixes the arm to the pole.

A specification for crossarms is given here-with.

SPECIFICATIONS FOR UNTREATED ARMS

These specifications cover painted crossarms made of Norway pine, yellow pine, cypress or Douglas fir.

Norway pine is understood to cover what is also known as red pine.

Yellow pine is understood to cover what is commonly known as Longleaf pine. It is understood that the term is descriptive of quality rather than of botanical species.

Douglas fir is understood to cover the timber known likewise as yellow fir, red fir, western fir, Washington fir, Oregon or Puget Sound fir or pine, Northwest and West Coast fir.

Cypress is understood to cover the timber known as red cypress.

General

The specifications and drawing are intended to include all instructions necessary for the manufacturer to guide him in his work. They are intended to coöperate with and supplement each other, so that any details indicated in one and not in the other shall be executed as if indicated in both.

All material and workmanship, unless otherwise specified, shall be of the best commercial grade.

Material

All crossarms shall be made of thoroughly air-dried, or kiln-dried, straight-grained wood of the kind contracted for.

Crossarms shall be of the style and dimensions shown. Figures on the drawing shall be followed in preference to scale measurements.

Quality

Pith Heart.—Cypress crossarms shall be free from pith heart.

Sapwood.—Cypress crossarms shall be free from sapwood. Norway pine, yellow pine, and Douglas fir crossarms may contain sapwood, provided it is clear and does not form over fifteen (15) per cent. of the cross-section of the crossarm. Crossarms shall be shaped so that the sapwood shall be on the top or the sides of the crossarms.

Grain.—All crossarms shall be reasonably straight grained. The grain shall not depart from parallelism to any edge of the crossarm by an amount greater than one (1) inch to three (3) feet length of crossarm.

Pitch Pockets.—All crossarms shall be free from pitch pockets exceeding five (5) inches in length and one-quarter (¼) of an inch in width, and from all pitch pockets which enter the pin or bolt holes on the top or sides of the crossarm.

Knots.—All crossarms shall be free from loose or unsound knots.

Wane.—All crossarms shall be free from wane.

Shakes.—All crossarms shall be free from through shakes, and from other shakes or checks exceeding three (3) inches in length.

Warp.—A straight edge laid lengthwise on the concave side of a seven (7) or a six (6) foot crossarm shall not show an offset

greater than one (1) inch on the seven (7) foot crossarm and greater than three-quarters (¾) of an inch on the six (6) foot crossarm. No crossarm shall be twisted, or bent in more than one direction or bent in one direction on edge.

Loose Heart.—All crossarms shall be free from loose hearts.

Rot.—All crossarms shall be free from rot, dote or red heart.

Worm Holes.—All crossarms shall be free from worm holes.

Inspection

All crossarms shall be inspected for dimensions and defects outlined under "Quality" before painting.

The spacing of the pin and bolt holes shall be within the limits shown on drawing.

Pin and bolt holes shall be tested with steel gauges and shall take gauges as follows:

• **Pin Holes.**—. . . . .-in. gauge without forcing but not a . . . .-in. gauge.

Middle-Bolt Hole.—. . .-in. gauge, without forcing.

Brace-Bolt Holes.—. . .-in. gauge, without forcing.

All crossarms not conforming to these requirements shall be rejected.

The pin and bolt holes shall be smooth and the arms shall not be badly splintered where the bits have broken through.

The brace-bolt holes shall not be drilled through the pin holes.

Storage

After the crossarms are shaped they shall be stacked in cross-piles on skids in such a manner as to insure good ventilation. The stacks shall be roofed to prevent the penetration of rain, or the direct action of the sun.

Hardware.—The hardware used on pole lines comprises the following:

1. Bayonet for ground wire.
2. U-bolt for ground wire.
3. Through bolts to hold bayonet to pole.
4. Through bolts to hold pole-head pin to pole.

(In some designs, one of the bolts in item 3 serves as a bolt for item 4.)

5. Washers for items 3 and 4.

6. Nuts for items 2, 3 and 4.
7. Lag screws for braces at crossarms.
8. Lag screws for braces on pole.
9. Braces.
10. Main crossarm bolt with nut and two washers.

The figures which follow, illustrating designs for pole heads, indicate the use of these various parts.

All hardware should be galvanized. The added cost is small and the injury to the parts of the pole head from continually forming rust may be considerable.

The following specification should apply to all galvanized hardware, guy wires, or other items which enter into the make-up of a line.

TESTS FOR HOT GALVANIZED IRON OR STEEL

(*a*) **Coating.**—The galvanizing shall consist of a coating of pure zinc of uniform thickness, and so applied that it adheres firmly to the surface of the iron or steel. The finished product shall be smooth.

(*b*) **Cleaning.**—The samples shall be cleaned before testing, first with carbona, benzine or turpentine, and cotton waste (not with a brush), and then thoroughly rinsed in clean water and wiped dry with clean cotton waste.

The samples shall be clean and dry before each immersion in the solution.

(*c*) **Solution.**—The standard solution of copper sulphate shall consist of commercial copper sulphate crystals dissolved in cold water, about in the proportion of 36 parts, by weight, of crystals to 100 parts, by weight, of water. The solution shall be neutralized by the addition of an excess of chemically pure cupric oxide (CuO). The presence of an excess of cupric oxide will be shown by the sediment of this reagent at the bottom of the containing vessel.

The neutralized solution shall be filtered before using by passing through filter paper. The filtered solution shall have a specific gravity of 1.186 at 65°F. (reading the hydrometer at the level of the solution) at the beginning of each test. In case the filtered solution is high in specific gravity, clean water shall be added to reduce the specific gravity to 1.186 at 65°F. In case the filtered solution is low in gravity, filtered solution of a

higher specific gravity shall be added to make the specific gravity 1.186 at 65°F.

As soon as the stronger solution is taken from the vessel containing the filtered neutralized stock solution, additional crystals and water must be added to the stock solution. An excess of cupric oxide shall always be kept in the unfiltered stock solution.

(*d*) **Quantity of Solution.**—Wire samples shall be tested in a glass jar of at least two (2) inches inside diameter. The jar without the wire samples shall be filled with standard solution to a depth of at least four (4) inches. Hardware samples shall be tested in a glass or earthenware jar containing at least one-half (½) pint of standard solution for each hardware sample.

Solution shall not be used for more than one series of four immersions.

(*e*) **Samples.**—Not more than seven wires shall be simultaneously immersed, and not more than one sample of galvanized material, other than wire, shall be immersed in the specified quantity of solution.

The samples shall not be grouped or twisted together, but shall be well separated so as to permit the action of the solution to be uniform upon all immersed portions of the samples.

(*f*) **Test.**—Clean and dry samples shall be immersed in the required quantity of standard solution in accordance with the following cycle of immersions.

The temperature of the solution shall be maintained between 62 and 68°F. at all times during the following test.

First—Immerse for 1 min., wash and wipe dry.

Second—Immerse for 1 min., wash and wipe dry.

Third—Immerse for 1 min., wash and wipe dry.

Fourth—Immerse for 1 min., wash and wipe dry.

After each immersion the samples shall be immediately washed in clean water having a temperature between 62 and 68°F., and wiped dry with cotton waste.

In the case of No. 14 galvanized iron or steel wire, the time of the fourth immersion shall be reduced to ½ min.

(*g*) **Rejection.**—If after the test described in Section "*f*" there should be a bright metallic copper deposit upon the samples, the lot represented by the samples shall be rejected.

Copper deposits on zinc or within 1 in. of the cut end shall not be considered causes for rejection.

In the case of a failure of only one wire in a group of seven

wires immersed together, or if there is a reasonable doubt as to the copper deposit, two check tests shall be made on these seven wires, and the lot reported in accordance with the majority of the set of tests.

NOTE.—The equipment necessary for the tests herein outlined is as follows:

Filter paper.
Commercial copper sulphate crystals.
Chemically pure cupric oxide (CuO).
Running water.
Warm water or ice as per needs.
Carbona, benzine or turpentine.
Glass jars at least 2 in. inside diameter by at least $4\frac{1}{2}$ in. high.
Glass or earthenware jars for hardware samples.
Vessel for washing samples.
Tray for holding jars of stock solution.
Jars, bottles and porcelain basket for stock solution.
Cotton waste.
Hydrometer, large size with long scale.
Thermometer with large Fahrenheit scale.

Braces.—Table 15 herewith, gives the sizes and weights of standard crossarm braces. The cost of these ranges from 3 to 4 cts. per pound.

TABLE 15.—WEIGHTS OF STANDARD CROSSARM BRACES

Size	Wt. per 1000 Pcs.
$20 \times 1\frac{7}{32} \times \frac{7}{32}$ in.	1420 lb.
$22 \times 1\frac{7}{32} \times \frac{7}{32}$ in.	1560 lb.
$24 \times 1\frac{7}{32} \times \frac{7}{32}$ in.	1700 lb.
$26 \times 1\frac{7}{32} \times \frac{7}{32}$ in.	1840 lb
$28 \times 1\frac{7}{32} \times \frac{7}{32}$ in.	1980 lb.
$30 \times 1\frac{7}{32} \times \frac{7}{32}$ in.	2120 lb.
$20 \times 1\frac{1}{4} \times \frac{1}{4}$ in.	1670 lb.
$22 \times 1\frac{1}{4} \times \frac{1}{4}$ in.	1835 lb.
$24 \times 1\frac{1}{4} \times \frac{1}{4}$ in.	2000 lb.
$26 \times 1\frac{1}{4} \times \frac{1}{4}$ in.	2165 lb.
$28 \times 1\frac{1}{4} \times \frac{1}{4}$ in.	2335 lb.
$30 \times 1\frac{1}{4} \times \frac{1}{4}$ in.	2500 lb.

Reinforced-concrete Poles.—Several successful high-tension lines have been placed on steel reinforced-concrete poles. Obviously, a concrete pillar of any desired size, height and strength

can be built, with internally threaded tubes or heavy nuts, cast in the concrete for the reception of studs to which the crossarms, or a framework of any kind, can be bolted. A concrete pole is the only permanent form of support that has been used for transmission lines. The author is convinced that when designers of transmission lines become better acquainted with the possibilities of reinforced concrete, poles made of this material will be universally adopted. If the line voltages require the use of suspension insulators, a steel crossarm—either an angle or a channel—may be placed at a proper elevation, and of sufficient length to allow the maximum "swing" of the insulator string with ample clearance between line and pole.

If poles are spaced 300 ft. apart or, approximately, 17½ poles per mile, they need be only 46 to 48 ft. high to carry lines on a 3-ft. length of insulator string and give a maximum ground clearance of 20 ft. The cost of such poles, placed, should not exceed $50 or less than $900 per mile. This is for poles of sufficient strength to carry a circuit of three 0000 wires, and to take the stresses imposed by a wind pressure of 10 lb. per square foot and a longitudinal stress due to breakage of two wires. For the latter abnormal condition, a stress of 25,000 lb. per square inch in the steel reinforcement is assumed.

In view of the discussion of reinforced concrete and the formulæ given therein (see Chap. VII, Vol. I, "Dams"), there is no occasion to repeat them here.

The forces acting on poles have been set forth in the previous discussion of wood poles. With the data given in these portions of this work, any engineer can easily compute the cross-section of concrete and the amount of reinforcement required at any point along the length of the pole.

In addition to the longitudinal steel for reinforcement against the cantilever stresses to which the pole is subject, some circumferential, or hoop steel is required to resist torsional stresses which will be set up if breakage of wires occurs. These circumferential hoops serve also, as construction rods to separate and hold in place the longitudinal steel when the concrete is poured. The best form of reinforcement is heavy steel wire mesh, in as many rolls, or layers, as may be required to give the proper cross-section of steel. If more than three rolls, or layers, are required, the additional steel necessary may be in the form of rods.

One of the chief factors of cost of reinforced concrete poles is

the expense of handling them. They are very heavy, and to distribute and set them, is costly. Hence, they should be made as near the place of setting as possible. Poles have been made individually, in place, being cast vertically in the previously excavated hole. This, however, is more costly than making the poles in considerable numbers, at some convenient place, then moving and setting them, just as wood poles are.

In order to reduce the cost and weight, the stress in the concrete for the maximum condition of loading, should be taken as high as safety will allow, say, 700 lb. per square inch, which is not an excessive stress for abnormal conditions of loading. Also, for maximum loading, the steel may be stressed up to 40 per cent. of its elastic limit, so that steel having an elastic limit of 50,000 lb. per square inch may be stressed up to 20,000 lb. per square inch under abnormal loading.

The quantity of materials and the weight can be reduced by making the poles hollow, a collapsing form being used to make the inner space.

Many forms of reinforced-concrete poles have been designed, but at the present time the section most generally employed is square, having chamfered corners.

The weights of poles of certain given dimensions are as follows: Pennsylvania R. R., Meadows Division. Poles to resist transverse load of 6000 lb. applied 6.5 ft. from the top. Section square with chamfered corners. Taper, 1 in 120.

Weight of 35-ft. pole	5,300 lb.
Weight of 40-ft. pole	7,600 lb.
Weight of 65-ft. pole	17,300 lb.

Mr. Alfred Still states that these weights are excessive because of the great length of pole buried in the ground which was necessary owing to the softness of the swamp earth.

He also states that for ordinary conditions the weight of a 30-ft. pole would not exceed 2500 lb. and that of a 35-ft. hollow pole should not exceed 2000 lb.

Roughly, the cost of reinforced-concrete poles—exclusive of distribution and setting—ranges from 35 cts., to $1.00 per pound weight.

The economics of pole design depend on the relative costs of steel and concrete, and the most economical design is fixed by the local conditions.

Pole Heads.—Figures 111 to 122 show various designs of pole heads for transmission lines. Most of these are obvious without any description.

Figure 120 shows a road crossing pole with a grounded wire netting to catch and retain any broken wire. Transposition pole heads are made in the same way of two poles with the two top insulators and the lower middle one on the crossarm, as shown in the figure.

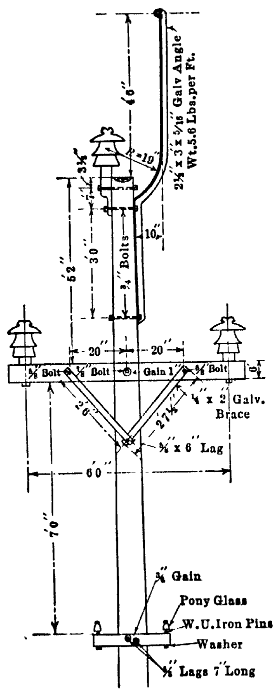


FIG. 111.—Pole head.

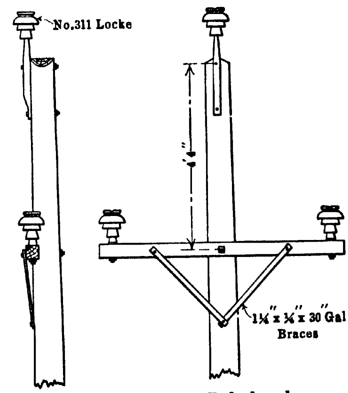


FIG. 112.—Pole head.

Pivot poles are those at which the line makes a change in direction and, hence, the stresses set up by the wires are much greater than those on standard pole heads. To resist these forces, two crossarms and two insulators, per wire, are fastened to a pair of poles as shown in Fig. 119.

Figure 122 shows a method of taking a branch off from the main line by dropping vertical connecting wires down to disconnecting switches placed at an elevation 17 ft. 6 in. below the main

line. From the disconnecting switches the branch wires go to the branch pole head as shown.

Figure 116 shows an ingenious arrangement of two diagonally placed crossarms carrying suspension insulators, the line voltage

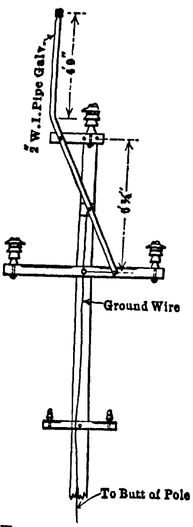


FIG. 113.—Pole head.

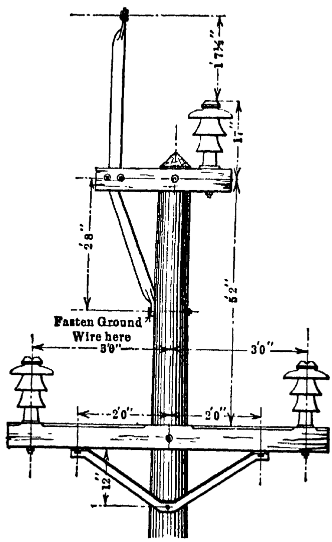


FIG. 114.—Pole head.

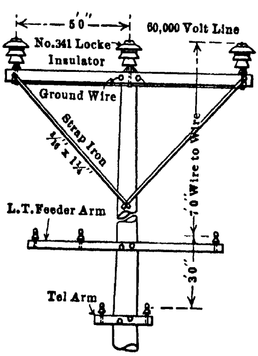


FIG. 115.—Pole head.

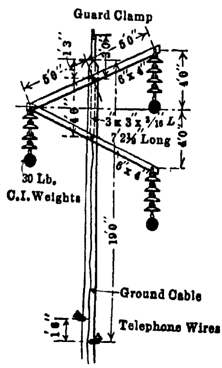


FIG. 116.

being 88,000 volts. To prevent the wind pressure from swinging the lines too near the poles, a 30-lb. cast-iron weight is hung below each wire, as shown.

Figure 117 is a strain or anchor pole for the line run on the pole heads shown in Fig. 116. Fig. 118 is another form of anchor pole. Fig. 121 shows a method of making a 90° turn with a heavy line.

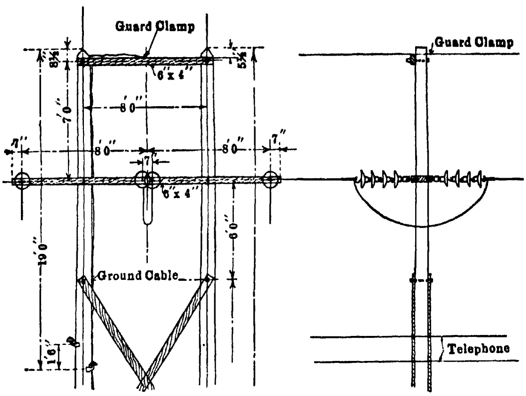


FIG. 117.

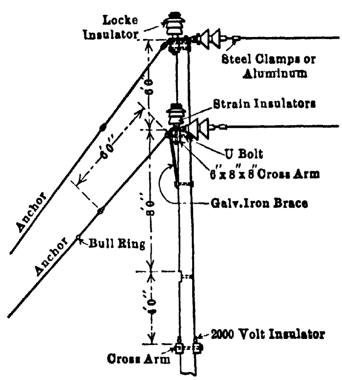


FIG. 118.

Figure 123 shows a steel lattice pole equipped with two metal crossarms arranged to give a triangular relationship of wires. These are arranged to carry suspension insulators. The whole construction is clear from the figure.

Towers.—Steel towers are of many forms, and the views of designers have differed considerably regarding the most econom-

ical type of tower, as is evidenced by the numerous varieties now in use. However, the present tendency is to use a tower which has four legs, with cross-members at the bottom and a

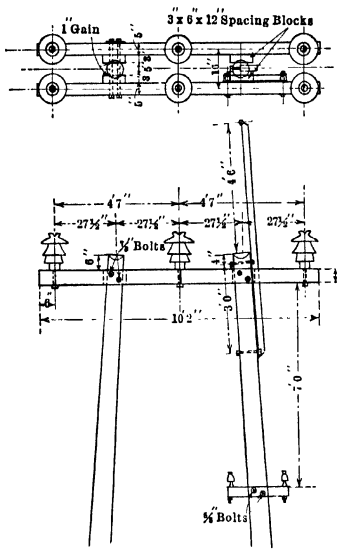


FIG. 119.—Pivot pole.

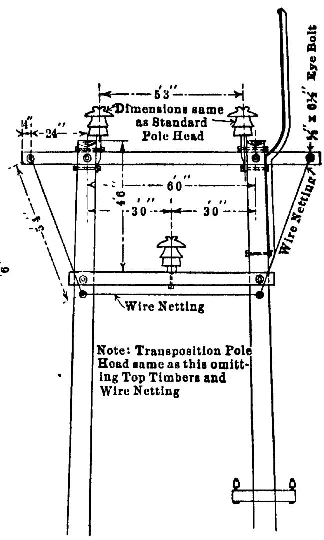


FIG. 120.—Road crossing pole head.

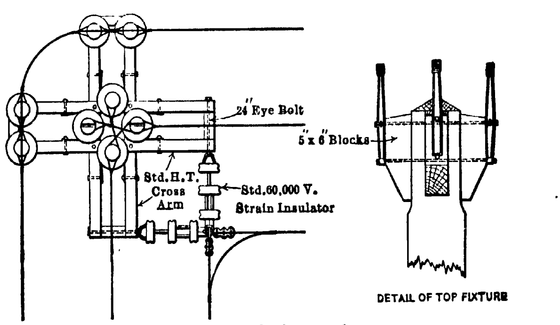
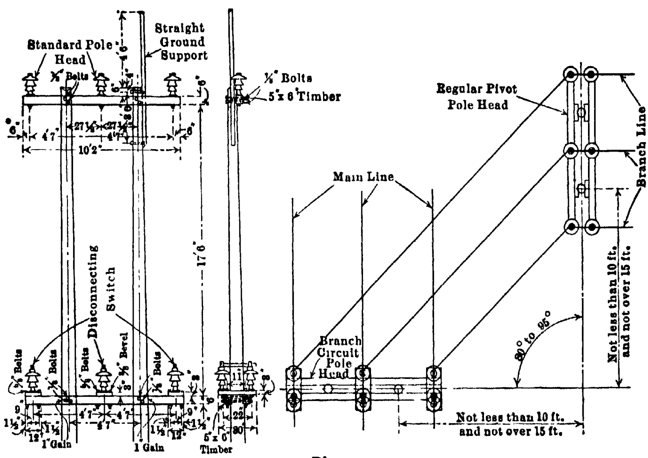


FIG. 121.—Pivot pole for 90 deg. turn.

spread at the base of from one-fourth to one-fifth the tower height.

There are two general types of towers, namely, the flexible and the rigid. The flexible tower is practically an *A* frame, which is rigid in the direction at right angles to the line, but is

capable of considerable deflection in the direction of the line. Fig. 124 shows one form of flexible tower. It resists all side forces due to wind pressure but inequalities in wire tension are met and equalized by a movement of the tower in the direction of the heavier strain. They are better adapted for lines supported on rigid insulators, as shown in the figure, than for suspension insulator lines. Some lines have been built with rigid towers 1500 ft. apart which serve as anchor towers, the line wires being fastened to these by a string of strain insulators, and in the middle of each of these long spans a low-cost, flexible tower is placed. In any line supported on flexible towers, equipped with



Plan

FIG. 122.—Pole head for branch circuits.

suspension insulators, the overhead ground wire is depended on to maintain them in a vertical position, and, sometimes, additional guys are run to ground anchors. In any case, rigid anchor towers must be placed at intervals in the line.

The most common form of rigid tower is the four-legged, square tower. In practically every case, they are thoroughly galvanized and are erected by using galvanized bolts to fasten the members together. The stresses which they have to resist have been given in the first part of this chapter. It is outside this discussion to enter into the question of tower design, but there are a few limiting factors which the engineer purchasing towers should

require of the manufacturer. The stresses acting are difficult to compute for each individual member and it has become common practice to determine the strength of towers by erecting a sample one and applying a force to it, at, or near, its top, and increasing this force until a distortion or rupture occurs. It

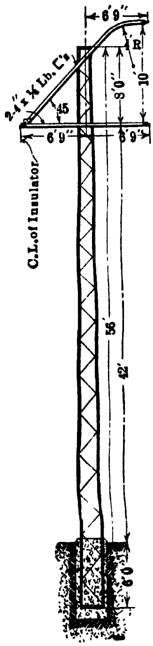


FIG. 123.—Detail of 56-ft. steel pole.

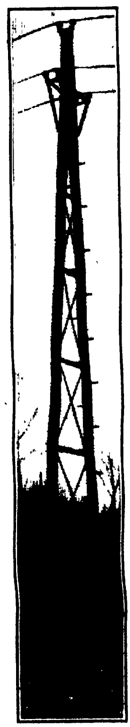


FIG. 124.—Flexible steel tower.

is customary to assume a breakage of one or more wires and determine the resulting distortional stresses set up and then to apportion this total stress equally among the four corner posts. These relations are expressed as follows:

If P = unbalanced force acting at end of crossarm.

a = distance from end of crossarm to center of tower, in feet.

b = distance from side of tower body to axis of the tower, in feet.

Then $p = \frac{P}{4}$ = force applied by P at each corner post, as a bending force acting on body of tower.

and $p_t = \frac{Pa}{8b}$ = torsional force applied at each corner post to twist body of tower.

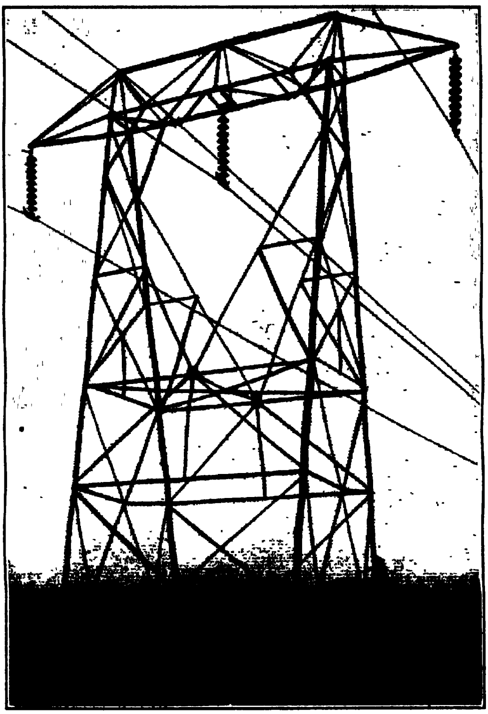


FIG. 125.—Steel tower for single circuit.

The unit stresses which are assumed in the preliminary designs are as follows:

Tension: 12,000 to 20,000 lb. per square inch.
Shear: 12,000 to 20,000 lb. per square inch.
Bearing: 16 000 to 30,000 lb. per square inch.

$$\text{Compression: } 20,000 - \frac{L}{R} \text{ to } 26,000 - 90\frac{L}{R}$$

L = unsupported length of member, in inches.
R = least radius of gyration of section, in inches.

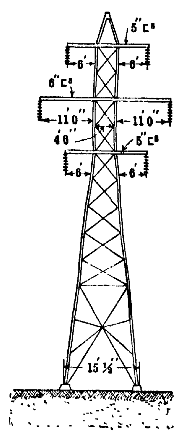


FIG. 126.—Two-circuit tower.

L and R are so limited that for main members $\frac{L}{R}$ does not exceed 125 to 180 and for any secondary members $\frac{L}{R}$ does not exceed 150 to 220.

For a double-circuit tower, the length of the top and bottom crossarms should be as short as possible to meet the conditions of safe clearance of the line when the insulators are blown in toward the tower. The middle crossarm should be made from 5 to 10 ft. longer than the top and bottom arms, so that the wires and insulators on the middle arm lie in vertical planes considerably removed from the planes of the wires on the top and bottom arms. In case of excessive sag of any span, due to ice loading or insulator breakage, there will be no danger of its contacting with the wire below it. This arrangement allows a reduction in the height of the tower because the clearances between the crossarms may be reduced. Where a single circuit

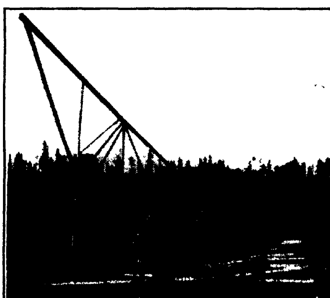


FIG. 127.—Assembling steel tower.

FIG. 128.—Erecting completed tower.

only, is carried on the tower, the best arrangement is one crossarm, the three wires being in the same horizontal plane. For durability, no material should be used in the make-up of the tower less than $\frac{3}{16}$ in. in thickness, regardless of the unit stresses in it.

The maximum side deflection of the insulator string should be taken as not less than 50°. It is claimed that under gusts of wind, the insulator will swing as much as 60° from the vertical.

Figure 125 shows a tower carrying one circuit only on a single crossarm. Fig. 126 is the outline of a tower carrying two circuits, the middle crossarm being longer than the upper and

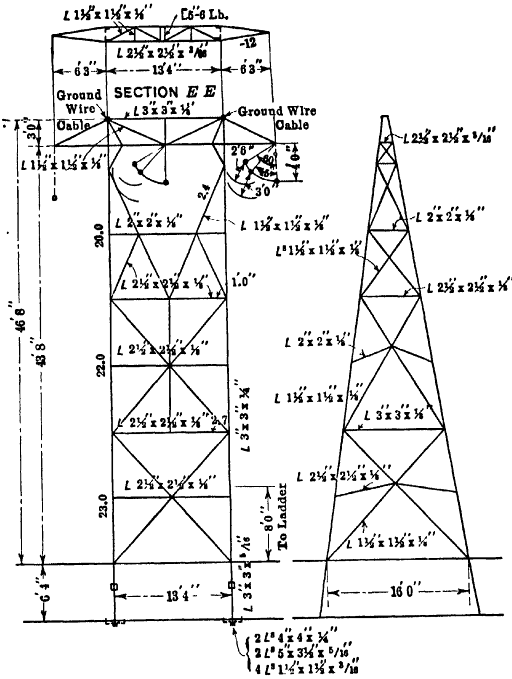


FIG. 129.—General dimensions of 53-ft. single-circuit tower.

lower one. Fig. 127 shows a tower being assembled for erection and Fig. 128 shows the method by which it is raised into position on its foundation by means of a gin pole and wire cables. As an indication of the sizes of structural steel used, the dimensions of a 52-ft. tower are shown in Fig. 129. In Fig. 130 is shown the head of an anchor tower with the strain insulators.

The general tendency is to design towers so that they will have the strength to resist, as cantilevers, almost any imaginable

force which may be applied at the top by abnormal conditions of wind pressures, ice loading or breakage of wires, these occur-

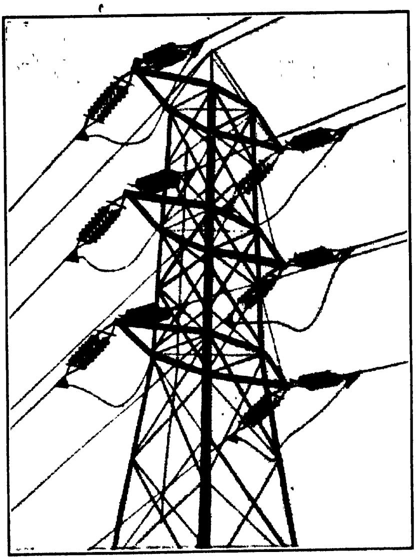


FIG. 130.—Top of anchor tower.

ring independently or together just as the views of the designer may happen to suggest. A very much cheaper structure and one equally stable to resist any stresses which may be imposed on it can be made by treating the tower as a support only, and carrying heavy guy wires from secure ground anchorages to points near the top. The guy wires will oppose all forces which are not vertical and relieve the tower of any cantilever stresses. While this type is the normal and rational form of steel-tower installation, it is not usual practice, and it is not customary to guy towers, except occasionally, where the direction of the line changes and a guy wire is placed to oppose the side pull of the line wires. It is difficult to assign a reason for the common practice of constructing heavy steel towers, large and strong

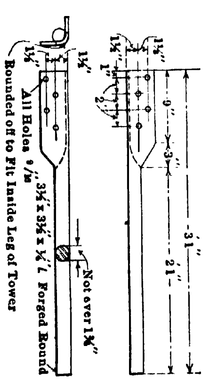


FIG. 131.—Rock footing tower anchor.

enough to act as cantilevers when it is so obvious that nothing is gained by this practice. A galvanized-steel guy wire will have as long a life as any of the thin rolled-steel sections used for

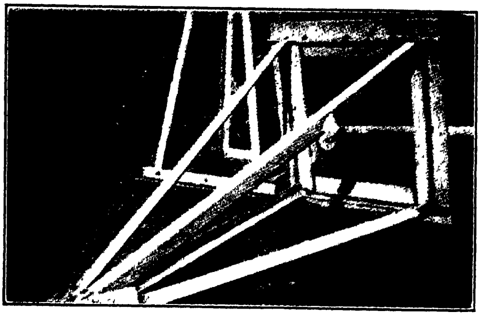


FIG. 132.—Steel frame tower footing.

struts and counterbraces, so that it cannot be a question of durability. The only overturning forces which act on a tower are transmitted to it by the overhead wires and why a guy wire is not good enough to oppose the stress set up by a transmission wire, is beyond the power of the author to explain. It is probable, however, that as more engineers enter the transmission field and as investors become more familiar with the subject and understand that certain expenditures are made simply because a sort of fashion, instead of engineering economics, is the basis of design, more rational ideas will prevail and the design of steel towers will be radically changed, if they are used at all.

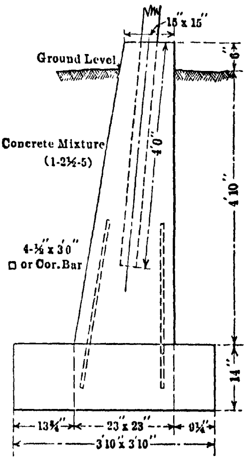
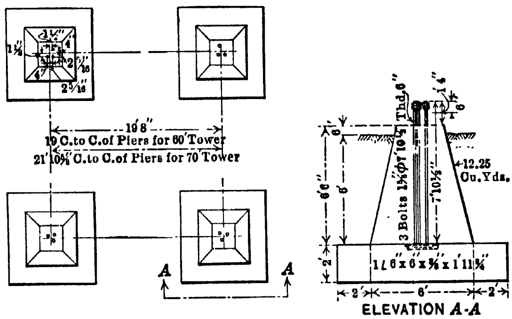


FIG. 133.—Concrete footing for 75-ft. double-circuit tower.

Tower Foundations.—The form of foundation used to support towers depends largely on the character of the soil. Where it is heavy and clayey, metal footings sunk into the earth may be used. It, however, is usually better to place a concrete pillar under each corner post and accurately level the tower footing on the upper surface and afterwards grout in

between the bottom of the tower footing and the top of the pier. There are as many varieties of tower footings as there are of towers and it is possible to depict only a few here. Fig. 131 shows a



Tower footing
FIG. 134.—Masonry plan and anchor bolts.

footing used where towers are set on rock. The rounded portion is sunk into holes drilled in the rock and securely grouted in. The corner posts of the towers are bolted to the sections which

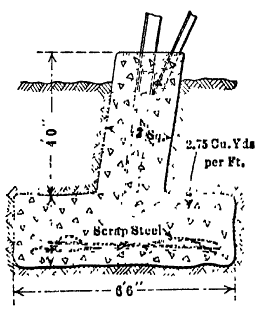


FIG. 135.—Stub footing for angle tower.

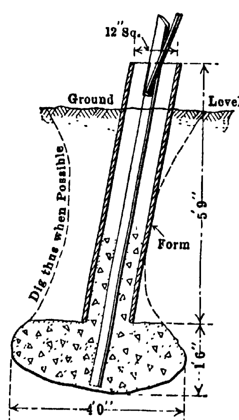


FIG. 136.—Tower footing.

have been forged into the form of an angle. In setting these, it is essential that they be accurately leveled before the grout hardens. A form of steel frame for footings is shown in Fig. 132.

These frames are sunk into holes made in the earth, the holes filled up and well tamped, and the corner posts of the tower are bolted to the projecting gusset plates shown at the bottom of the picture.

In designing any form of footing, the uplifting force which may be imposed at the bottom of the corner posts, due to forces exerted at the top by wind pressure or breakage of conductors, should be computed, and the footing made amply strong against movement under the maximum uplift to which it can be subjected.

The details of several forms of concrete footings are shown in Figs. 133, 134, 135 and 136.

In computing the wind pressure acting against the tower, it is customary to assume the pressure per square foot of solid area, as $0.004V^2$, V being the wind velocity in miles per hour. Twenty to 22 lb. per square foot, are the highest values taken, and some designers assume 13 to 14 lb. per square foot as the limiting wind pressure.

GENERAL SPECIFICATION FOR STEEL TOWERS

Open Sections.—Structures shall be so designed that all parts will be accessible for inspection, cleaning and painting.

Pockets.—Pockets or depressions which would hold water shall have drain holes, or be filled with waterproof material.

Splices.—Where a lap splice is used in leg angles the back of the inside angle shall be chamfered to clear the fillet of the outside angle.

Bolts.—The minimum size of bolts will be 5/8 in. diameter. The bolts have rolled threads, but must be full size in the shank. All bolts connecting the different parts of the tower together shall be of the same diameter and of as few different lengths as practicable. The shank of the bolt shall be long enough to extend through the members connected. A washer at least 1/8 in. thick shall be used under the nut.

Bolt Holes.—The punched holes shall not be more than 1/16 in. larger than the nominal diameter of the bolt.

Similarity.—In the case of square towers all four faces shall be made alike, as nearly as practicable.

Minimum Number of Parts.—Preference will be given to the designs that have the least number of parts.

Minimum Thickness.—The minimum thickness of material of any member for painted towers shall be 1/4 in., but, if the material

is to be galvanized, the minimum thickness of material in the legs shall be $\frac{1}{4}$ in., and that for any other members having calculated stress shall be $\frac{3}{16}$. Those having nominal stress only shall have a minimum thickness of $\frac{1}{8}$ in.

Ratio of Slenderness.—In compression members the ratio of the unsupported length divided by its least radius of gyration shall not exceed the following:

Legs	140
All other members having calculated stress	200
Members having nominal stress only	220

Use of Rods.—Rods will be allowed only where proper provision is made for tightening up same in the field.

Ground Wire Clamp.—The ground wire clamps will be considered a part of the towers and furnished with them by the contractor. They shall be of such design as will firmly hold, but not injure the cable.

Insulator Connection.—The contractor for the towers shall provide the necessary holes in the steel work of the towers for the connection of the insulator.

Ladder.—At least one leg of the tower shall be provided with steps. These steps, if made of bolts, shall be at least $\frac{5}{8}$ in. diameter and not more than 16 in. centers, starting 8 ft. from the ground.

Painting.—If the towers are to be painted, all parts of the tower shall receive one coat of best quality paint at the shop before shipping.

Galvanizing.—If material is to be galvanized, all parts of the tower except bolts and other special parts, shall be galvanized by the hot dipping method as the last process of fabrication. The bolts and other parts may be sherardized. All galvanizing shall be done in accordance with the specifications of the National Electric Light Association of 1911.

Material.—The steel used shall be made by the Open Hearth process and conform to the latest specifications for structural steel for buildings, as adopted by the American Society for Testing Materials.

Drawings.—All parts forming a tower shall be made in accordance with approved drawings.

Workmanship.—The workmanship and finish shall be equal to the best modern practice.

Marking.—Each separate member shall be plainly stamped with a number. All like parts shall have the same number, the mark being in the same relative position on each piece, but all different members shall have different numbers to distinguish them. This marking shall be stamped into steel before galvanizing or painting, with numbers at least 3/4 in. high, in such manner as to make them plainly visible after galvanizing or painting.

Shipping.—Unless otherwise specified, all parts of towers will be shipped unassembled, to be bolted together in the field. All like parts of one tower shall be bundled together at the shop before shipping, except such parts as would make too heavy a bundle for convenience in handling. Bolts and other small parts shall be shipped in bags or boxes strong enough to resist the necessary rough handling.

Inspection.—On request of purchaser the manufacturer shall furnish proper facilities to representative of the purchaser for the inspection of material and workmanship during the fabrication. The purchaser shall be notified well in advance of beginning the work in the shop in order that he may have an inspector on hand to inspect material and workmanship.

Assembling.—One of each standard line towers shall be assembled at the shop before shipment.

Test.—At request of purchaser, one each of the standard line towers shall be assembled and tested with loads as nearly as practicable like those for which the tower is designed, also if requested by purchaser the tower shall then be tested to destruction. The members forming the test tower will be selected at random from piles of similar members. The towers to be tested shall be set on a foundation as nearly as practicable like that to be used in the field. Unless otherwise agreed upon all tests will be made at the expense of the purchaser.

Foundations.—The foundations shall be designed to withstand two and one-half times the load coming on them without injurious movement, care being taken that they resist both the horizontal and vertical loads. If steel footings are used, it may be assumed that earth weighs 100 pounds per cubic foot, and that the base will engage the frustrum of an inverted pyramid of earth whose sides have an angle of 33° with the vertical. If concrete foundations are used the weight of a cubic foot shall be assumed at 140 lb. Material buried in concrete will be left black, except

where stub angles are used, in which case, the stub angle be galvanized or painted from the top down to a distance of 18 inches below top of concrete.

Spacing of Towers.—The spacing of towers varies from 400 to 1000 ft. There is, of course, for any set of conditions, a spacing which is the most economical, and this should be worked out for each particular case. The most economical spacing may be determined, by assuming several different spans, finding the costs of towers, foundations, insulators and accessories per mile, for each span, and by this trial method the proper spacing is found. A somewhat better method is to plot a series of curves of tower, costs per mile for different spacings, using dollars as ordinates and distances apart of towers as abscissæ. The tower cost includes, of course, not only that of the tower itself, but also insulator, foundation and erection costs. This curve will

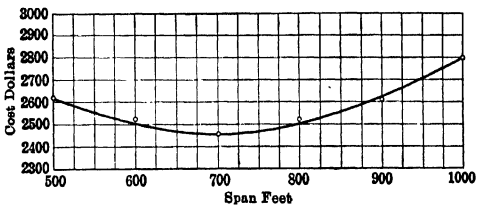


FIG. 137.—Cost per mile of towers and insulators, erected.

have a minimum point, and the spacing corresponding to this point is the most economical one. Fig. 137 shows a curve of this kind, based on prices of materials and labor for the year 1911. It shows the minimum cost to be for a spacing of 700 ft., amounting to $2460 per mile of tower line. The computations are exclusive of the cost of wires as these are practically constant for any given conditions of power transmission.

Notes on Transmission-line Economics.—Steel towers are inherently uneconomical as transmission-line supports. It is claimed, by engineers who advocate their use, that they are necessary for the long crossarm spans required by suspension insulators, and the suspension insulators are demanded by the voltage which must be used in order to keep the cost of the transmission conductors within the bounds of commercial possibility.

Suspension insulators can be successfully supported on poles

as has been proven in more than one instance. Furthermore, an increase in line voltage, resulting in a corresponding diminution of the cost of conductors, does not always produce a net decrease in the total line cost, although it generally will add to the complexities of the system and difficulties of operation. The cost of all accessory apparatus, such as insulators, lightning arresters, transformers, disconnecting switches, choke coils, oil-break switches, and, every other part of the transmission equipment, increases very rapidly as the voltage increases. Transformers for 110,000 volts cost 40 per cent. more than equivalent transformers for 70,000 volts, while electrolytic lightning arresters cost 50 per cent. more for the higher voltage.

If a lower-voltage line on poles costs about the same as a higher-voltage line on towers, the former is, financially, the preferable one, for in the one case the money would be invested, principally, in wires or cables with a small amount in poles, transformers and lightning arresters, while in the latter case, the money would be sunk in towers, transformers and lightning arresters.

Bare wires and cables have an intrinsic value and are not subject to depreciation. The prices of the metals may fluctuate but they represent convertible property which continues year after year with its value undiminished.

Fabricated materials, such as towers and electrical apparatus are subject to change, injury and even destruction, and each year their values are less than the preceding one.

Another factor is the use of aluminum wire. The price of aluminum is arbitrarily fixed by its producers, but, in recent years, it has been kept at an average of 23 per cent. below the prevailing cost of equivalent conductivity in copper. With towers spaced 600 ft. or more apart, the use of aluminum cable is impracticable, unless it have a steel core, for reasons elsewhere explained. This bimetallic wire costs nearly as much as copper and, for this reason, most of the long-span tower lines are of copper. With short-span lines, plain aluminum cable can be used and the full advantage obtained of the difference in price.

To make clear these several contrasting statements, a specific case is taken and the cost of the line and accessories computed for poles and towers.

The total cost of the line is not estimated as those portions which would be the same in either case are omitted, such as ground wire, and right-of-way. The inclusion of these would

not affect the comparison, and would add to the length of the computations.

The basic conditions which are assumed are:

Full normal load (peak) 12,000 kw.

Distance of transmission 120 miles.

These are large figures compared with the average transmission in America. One hundred and twenty miles is a long transmission and 12,000 kw. full load represents an annual delivery of energy equal to 42,000,000 kw.-hr. on the basis of a 40 per cent. load factor.

The other conditions assumed are as follows:

Power factor of load, 85 per cent.
Kv.a. transmitted, 14,100.
Frequency, 60 cycles.
Regulation to be 12 per cent. at full load.
28,000 kv.a. of transformer capacity required and 12 lightning arresters.
Volts for tower line, 110,000.
Separation of wires, 15 ft.
Volts for pole line, 70,000.
Separation of wires, 7 ft.
Tower spans, 750 ft.
Pole-line spans, 203 ft.

Strength of pole, or tower.

Factor of safety of 4, against side stresses due to wind load.
Factor of safety of 2, against stresses due to breakage of one wire.
Lowest point of wire, 20 ft. above ground.
Size of wire for 12 per cent. regulation 110,000 volts is 126,000 cir. mils, weighing 2060 lb. per mile.
Size of wire for 75,000 volts. This must be divided into two circuits.
Size for each circuit = 127,500 cir. mils. weighing 2080 lb. per mile.
Price of bare copper wire taken at normal figure of 16 cts. per pound.

Tower Line Costs.—Tower with foundations, insulators and fittings.

120 miles @ $2600 per mile	$312,000
360 miles wire, 741,600 lb. @ 16 cts	118,656
28,000 kv.a. transformers @ 1.40	43,200
12 lightning arresters @ $2000	24,000
Total	$497,856

Pole-line Costs.—Poles must be 45 ft. in length to carry three crossarms spaced 7 ft. 0 in. apart and must be set 7 ft. in the ground, so that height of lowest wire, at the pole, is 24 + 1 = 25 ft. above ground, the additional foot being the insulator height.

1.	Cost of pole gained and set	17.00
2.	Cost of three crossarms each 5 by 6 in., 15 ft. 0 in. long	3.00
3.	Cost of six insulators and pins @ 2.60	15.60
4.	Cost of braces, bolts, hardware, etc	1.80
5.	Cost of ground-wire bayonet	1.10
6.	Cost of labor on pole head	2.00
		40.50

Of these costs, items 1, 2, and 6, or a total of $22 per pole, depreciate at the same rate as the pole, *i.e.*, 10 per cent. per annum, while the rest, or $18.50 per pole, depreciates at the rate of 5 per cent. per annum.

Number of poles per mile, 26.

Number of poles in 120 miles, 3120.

Cost of Pole Line.—	
Items 1, 2 and 6.	
3120 @ $22.00	$68,640
Items 3, 4 and 5.	
3120 @ $18.50	$48,840
Wire	
720 × 2080 = 1,497,600 lb. @ 16 cts.	$239,616
28,000 kv.a. of transformers @ $1.00	$28,000
12 lightning arresters @ $1350	$16,200
	$405,296
Saving over tower-line cost	$92,560
Annual Charges, Tower Line.—	
Interest, 6 per cent. on $497,856	$29,871
Depreciation, on towers, transformers, and arresters = 5 per cent. on $379,200	$18,960
Depreciation on wire @ 1 per cent. on $118,656	$1,186
Total annual charges	$50,017
Annual Charges, Pole Line.—	
Interest @ 6 per cent. on $405,296 =	$24,318
Depreciation:	
10 per cent. on items,1, 2 and 6	$6,864
On items 3, 4, 5, transformers and lightning arresters = 5 per cent. on $93,040	$4,652
1 per cent. on wire	$3,473
Total	$39,307

Saving in annual charges over tower line is $10,710, or 5 per cent. on $214,000.

The comparison is not complete. Aluminum could be used on the pole line with 203-ft. spacing, giving a net reduction of at least 20 per cent. of the conductor costs, so that the cost of the line on poles would be $357,373 instead of $405,296, showing a saving in first cost, over the steel tower line, of $140,483. Also, the interest charges and wire depreciation, taken together, would be reduced $3354 by using aluminum, so that the annual charges of the pole line would be, in reality, $14,064 less than those of a tower line.

Unquestionably, there are distances of transmission and quantities of energy to be transmitted such that towers become necessary. That condition, however, is not inside 120 miles and 12,000 kw.

While continuity of service is one of the most desirable and necessary conditions of electrical supply, *absolute* continuity over a long period of years, with abnormal occurrences of temperature, sleet, burnt wires, high winds and other conditions which endanger a line, can not be obtained without an excessive investment. Interest and depreciation continue 365 days every year. The owners of the property must have some return for this investment. The question is, would not a lower-cost line, with an occasional interruption and its attendant loss, pay greater net returns to the investors. When the cost of insurance against failure of service costs more than the failure would, the investment has been carried too far. Also, the interest loss is a certainty, while the loss due to line failure is only a risk and may never occur. Engineers spending money for people who invest it in the hope of a reasonable income, should carefully analyze the financial factors, and their designs should be governed by the production of the greatest dividends from a given expenditure.

No money should be invested without the definite knowledge that each dollar expended will bring in an annual, net return, excepting only that money spent to insure the safety of human life. The specific application of these remarks is to the question of the strength of transmission-line supports, but they constitute a sound financial axiom that applies to every other part of the plant.

Also, it is a financial fallacy to allot a specific value to all energy lost in the transmission line or used in station auxiliaries.

Unless the station is fully loaded, the cost of the lost current is practically nothing. No costs in a water-power plant are proportional to the output. They are fixed, regardless of whether the station works on quarter load or full load, and if the water be plentiful and the total load within the generating capacity of the plant, energy losses do not represent any financial loss. Of course, when the commercial load overtaxes either the station equipment or the water supply, the condition changes and the losses immediately have a money value equal to the selling price of the energy consumed.

Since, in general, the transmission-line cost has a continuous interest charge against it, and the energy loss in it may represent a money value a small portion of each year only, it is good financial practice to make the full-load line losses as great as a reasonably satisfactory regulation will allow. Hence, the criterion for the size of wire is allowable regulation, not energy loss. Of course, this is a broad general statement subject to modification according to specific circumstances. If the added, actual earnings produced by increasing the size of wire above that required for regulation, will exceed the interest charges on the added investment, the larger wire should be used, otherwise, it should not be.

CHAPTER IX

ELECTRIC CIRCUITS

Continuous Currents.—A continuous current flows in one direction only, as distinguished from an alternating current which rapidly changes its direction of flow. Continuous, or "direct" currents are used for power work of all kinds and for charging storage batteries. For electroplating and the excitation of field magnets of generators, continuous current, only, can be used. For electric traction, continuous current is far superior to alternating, and is almost universally used for this purpose.

The law that governs current flow in conductors, no matter whether continuous or alternating, is Ohm's law and is

$$I = \frac{E}{R}$$

I = current in amperes.
E = electromotive force, in volts.
R = total resistance in ohms.

E is not necessarily the electromotive force impressed on the circuit by the dynamo. It is, if no other e.m.f. acts on the circuit. If other e.m.fs. act, E is the resultant of all the e.m.fs. in the circuit.

From this law follows that $E = IR$ and $R = \frac{E}{I}$. Also, the power in a circuit, or delivered by a circuit, is EI, in volts and amperes.

The product of 1 volt by 1 ampere = 1 *watt.*
1000 watts = 1 kilowatt, abbreviated kw.
746 watts = 1 horsepower, and 1 kw. = 1.34 hp.

If E volts are required to force 1 amp. through a wire, the energy used in the wire is EI watts, and since $E = RI$, the energy may be expressd as I^2R. This energy goes into heat and, therefore, the temperature of a conductor carrying current is always higher than that of the surrounding air.

The computation of continuous-current circuits is very simple.

If kw. = energy to be transmitted in kilowatts.
E = generator voltage.
D = distance of transmission in feet.
p = per cent. allowable loss of energy in circuit, expressed as a decimal fraction.

$$I = \text{amperes} = \frac{\text{kw.} \times 1000}{E}$$

Then, for copper wire:

$$\text{c.m.} = \frac{I \times 2D \times 11}{pE}$$

c.m. = circular mils, which is a designation by which the size of wire is fixed.

The circular mils are proportional to the area of the wire, and cir. mils = $(1000d)^2$ where d = diameter in inches. Thus a wire 0.25 in. in diameter has an area = $(0.25 \times 1000)^2 = 62{,}500$ cir. mils.

The actual area of a wire in square inches is

$$a = \frac{\text{cir. mils} \times 0.7854}{10^6}. \qquad (42)$$

Wires and cables are given arbitrary gauge numbers, a certain diameter and area corresponding to a given gauge number.

Tables are given at the end of Chapter X, which show the electrical constants and areas of the commercial sizes of wires and cables.

As an example, take the computation for the size of wire necessary to transmit 500 kw. a distance of 10,000 ft., the generator voltage being 550 and the allowable loss 9 per cent.

$$I = \frac{500 \times 1000}{550} = 910 \text{ amp.}$$

$$\text{c.m.} = \frac{910 \times 2 \times 10{,}000 \times 11}{0.09 \times 550} = 4{,}000{,}000 \text{ cir. mils.}$$

This is equal to

$$\frac{4{,}000{,}000 \times 0.7854}{10^6} = 3.14 \text{ sq. in. of copper.}$$

These same formulæ apply to single-phase alternating currents when the load is non-inductive. In alternating-current circuits, secondary electromotive forces are set up which combine with the impressed voltage, and produce certain modifications of the foregoing simple formulæ.

Alternating Currents.—When an alternating e.m.f. is impressed on a circuit in which there is only resistance, the current will flow exactly in phase with, and in a quantity proportional at each instant, to the e.m.f. Fig. 138 shows this condition;

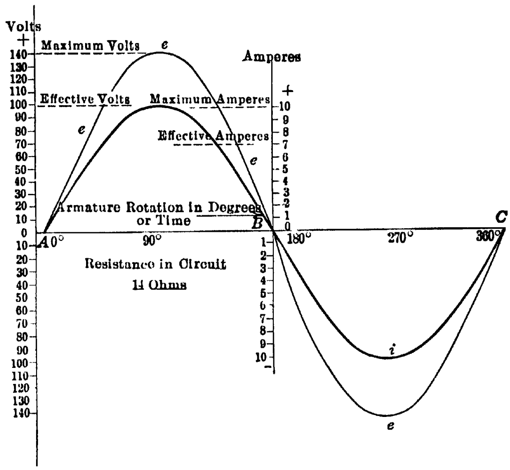


FIG. 138.—E.m.f. and current curves.

e,e,e,e is the impressed e.m.f. and *i,i,i,i* is the curve of current flow.

As may be seen, the current flow is exactly in phase with the e.m.f. and, at any instant, is equal to the e.m.f. at that instant, divided by the resistance.

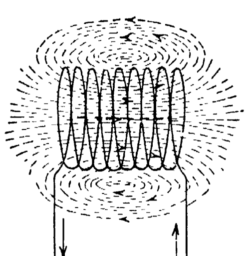


FIG. 139.—Lines of force in inductive coil.

Inductance.—If an inductance be inserted in the circuit, the current flow will be reduced, and the *impressed* e.m.f. at any instant, divided by the resistance, will not give the value of the current at that instant.

Consider an inductive coil, as shown in Fig. 139. If current flows through the coil, magnetic lines are set up threading the turns as shown. If the current should vary in intensity or direction, the number or direction of the lines of force will also change; this change in the magnetic lines taking place exactly with the current variation. Any change

in the number or direction of the lines of force threading a coil will produce an e.m.f. in the coil, just as the change in the number of lines of force through an armature coil produces an e.m.f. Also, the more rapid the change in current through the coil, the more rapid is the change in magnetization, and, therefore, the greater is the e.m.f. set up in the coil. The e.m.f. produced by the change in current is always in such a direction as to oppose this current change, and, therefore, when the current tends to decrease, assists it to continue flowing, and opposes the current flow when it begins to increase.

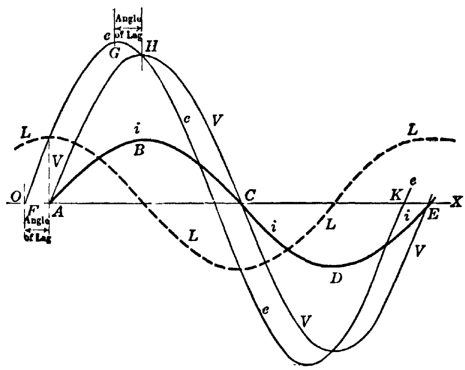


FIG. 140.—Effects of inductance and resistance.

If in Fig. 140 the curve i,i,i,i is drawn to represent the magnitude and direction of the alternating current to any arbitrary scale, the ordinates being amperes and the abscissæ units of time—say, hundredths of a second—the ordinate at any time will show the value of the current at that instant.

Assume that both a resistance and inductance are included in the circuit. The changes in the value of the current through the inductance coil will produce an e.m.f. in that coil. When the current is not changing—which condition exists when the crest of the wave is reached, as at B and D—the lines of force in the coil do not change and, consequently, the inductance e.m.f. is zero. The current changes most rapidly when it is passing through zero—that is, when crossing the zero line from + to − , or − to + , and since the lines of force also change most rapidly at this instant, the inductance e.m.f. is greatest.

The curve L,L,L,L is the inductance e.m.f. and plotted so that

it is zero at the time the current is maximum, and maximum when the current is zero. The distance from A to E represents a complete cycle, or, if referred to the armature which produces the current flow, this distance represents one complete revolution (bipolar machine) of the armature. This being 360°, and the inductance e.m.f. being one-fourth the distance from A to E behind the current, it is conveniently referred to as being 90° behind the current, *i.e.*, as the armature rotates, it passes through ¼ revolution, or 90°, after the current begins to start from zero, before the e.m.f. of inductance begins to rise in the opposite direction.

Since the current passes through a resistance, the e.m.f. which causes it to flow is equal, at any instant, to the value of the current at that instant, multiplied by the resistance. The curve V,V,V,V represents this e.m.f., which is in exact phase with the current. The impressed e.m.f. to cause the current flow must be equal to the e.m.f. V,V,V,V, plus an additional amount equal to the e.m.f. of the inductance at those times when the current is increasing, and less than V,V,V,V, at those times when the current is diminishing, because the e.m.f. of the inductance opposes change of current strength. By adding to the ordinates of V,V,V,V the corresponding ordinates of L,L,L,L, above the line O,X, and subtracting from V,V,V,V the corresponding ordinates of L,L,L,L, below the line O,X, where V,V,V,V is still above the line—in other words, taking the algebraic sum of the ordinates of the two curves—the curve e,e,e,e results, which shows the value and phase of the e.m.f., which the alternator must deliver to the line in order to send the current i,i,i,i through the resistance of the circuit and overcome the opposing inductance e.m.f. The presence, then, of an inductance in the circuit, adds an e.m.f. to the system, and the useful or active e.m.f. which sends current through the circuit is the *resultant* of the e.m.fs. acting. The current is always in exact phase with the resultant e.m.f., and is at any instant, equal to the resultant e.m.f. at that instant, divided by the resistance of the circuit.

Since e.m.fs. may be combined like other forces and the inductance e.m.f. is at 90° to the resultant e.m.f., it is convenient to make computations graphically as in Fig. 141. If IR represents the effective value of the resultant e.m.f., and E_L that of the inductance, and they be laid out to proper scale at 90° to each other as shown, the line AC will be the effective value of

the impressed e.m.f. The angle ϕ is called the angle of lag, and shows that the armature of the alternator supplying the impressed e.m.f. turns through an angle equal to ϕ from the position where its e.m.f. is zero, before the current begins to rise from zero. This is shown by Fig. 140. If FK represents the time of a complete revolution of the alternator armature, the impressed e.m.f. begins to rise from zero at F; but it passes through the time—or distance—from F to A before the current begins to rise, for the reason that not until A is reached is the alternator e.m.f. equal to the opposing e.m.f. of the inductance. FA, then, is the angle of lag, and equal to ϕ in diagram 141. If FK be called 360°, FA is the number of degrees of the angle of lag to the same scale. GH shows also the angle of lag, being the difference in time, or degrees, in which the impressed e.m.f. and current reach their respective maxima.

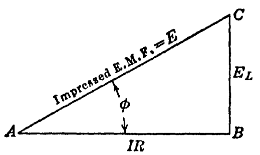


FIG. 141.—E.m.f. diagram.

From Fig. 141 it is also evident that the impressed e.m.f. is

$$E = \sqrt{(IR)^2 + E_L^2} \tag{43}$$

In Fig. 140 it will be found that at any instant, the value of the impressed e.m.f. is equal to the square root of the sum of the resultant e.m.f. squared and the inductance e.m.f. squared, if it be remembered that the value of the inductance e.m.f. becomes negative when on the opposite side of the line OX, from the resultant e.m.f.

The triangular diagram shown in Fig. 141 is merely a convenient method of calculating the relations between the various quantities and must not be confused with the actual effects which are taking place in the circuit. Also the use of the term "angle of lag" does not mean that the current lags behind the e.m.f. which causes it to flow. It lags behind the impressed e.m.f. and is ahead of the inductance e.m.f., but always in phase with the resultant e.m.f.

The value of the inductive e.m.f. is found as follows:

The unit of inductance is called the henry, and is equal to that inductance which will produce one volt when the current through the coil changes at the rate of one ampere per second. Since the voltage will vary directly as the rapidity of cutting of lines, and, therefore, with the rapidity of change of current, a coil of

1 henry inductance = L, would give 50 volts if the current should vary 1 amp. in $\frac{1}{50}$ sec., or would give 100 volts if the current should change 2 amp. in $\frac{1}{50}$ sec.

When an effective current of 1 amp., which follows the sine law, passes through one cycle per second, the rate of current change is 2π, or 6.28 amp. per second, from which it follows that the effective e.m.f. set up at the terminals of the inductance is

$$2\pi \times f \times I \times L \tag{44}$$

in which

f = number of cycles per second,
I = current in effective amperes,
L = coefficient of self-induction in henrys.

This coefficient 6.28 may be also arrived at in another way.

If a conductor is rotated in a magnetic field, it will cut all the lines of force twice in a complete rotation, and a loop or single turn—which is two conductors—will cut all the lines four times. The *average* voltage, therefore, of a rotating loop is $\frac{4 \times f \times N}{10^8}$, where f = frequency or number of rotations per second and N = total number of lines in the magnetic field. 10^8 is the coefficient to reduce the fundamental, or C.G.S., units to volts.

An alternating current or e.m.f. varies in value with the sine of the angle through which the loop rotates, reckoned from any fixed point in the circle in which it travels, and the *average* value of the sine through a half cycle is 0.6366 of the value of the maximum ordinate when the crest of the wave is reached.

The *effective* current, or e.m.f., is not the average, but is the square root of the mean square of the various values throughout the cycle, and this is equal to 0.707 of the maximum. The effective voltage, then, for a sinusoidal alternating e.m.f., no matter how produced, is

$$E = \frac{4 \times 0.707}{0.6366} \times \frac{f \times n \times N}{10^8} = \frac{4.44 fnN}{10^8} \tag{45}$$

n being the number of turns in the loop.

The maximum value of the e.m.f. is 1.415 times the effective value, and, in the case of an inductance, the voltage is produced by the change of current from zero to its maximum. Therefore, the voltage self-induced in a coil by a sinusoidally varying current is

$$E = \frac{4.44\ f\ n\ \Theta\ I_{max}}{10^8} \tag{46}$$

where I_{max} is the maximum value of the current, and Θ = number of lines of force produced per ampere of current flowing; $\therefore$ $\Theta I_{max.} = N$.

Since an inductance of 1 henry produces 1 volt for 1 amp. change in current through it in 1 sec., and a volt results from cutting 10^8 lines per second, it is evident that if a coil of one turn has 10^8 lines produced in it by 1 amp. flowing through it, it has an inductance of 1 henry. If the coil has 10 turns and 10^7 lines are produced in it by 1 amp., then the inductance is also 1 henry. From which it follows that the inductance of a coil in henries, may be expressed as the product of the number of turns multiplied by the number of lines produced by 1 amp., divided by 10^8 or

$$L = \frac{n\Theta}{10^8} \tag{47}$$

Substituting this value of L in equation (46), it becomes:

$$E = 4.44\, f\, LI_{max.} \tag{48}$$

$$I_{max.} = 1.415 \times I_{effective}.$$

If, now, the *effective* value of I be substituted,

$$E = 1.415 \times 4.44 \times fLI = 6.28\, fLI.$$

The coefficient of self-induction (L) is usually determined experimentally.

Referring again to Fig. 141, it is obvious that the tangent of the angle of lag, ϕ, is equal to $\frac{E_L}{IR}$. $E_L = 2\pi fIL$, whence,

$$\tan \phi = \frac{2\pi fLI}{RI} = \frac{2\pi fL}{R} = \frac{\omega L}{R} \tag{49}$$

where $\omega = 2\pi f$.

It is now easy to compute the angle of lag and current flow for any circuit, If the resistance be 20 ohms, L, 0.05 henrys, frequency 60 cycles and impressed e.m.f. 100 volts, what current will flow?

Volts to overcome resistance for 1 amp. flow = 20 volts.

Volts to overcome inductance for 1 amp. flow = $0.05 \times 6.28 \times 60 = 18.84$.

Volts impressed per ampere of flow = $\sqrt{(20)^2 + (18.84)^2} = 27.5$.

Therefore,

$$I = \frac{100}{27.5} = 3.64 \text{ amp.}$$

Tangent angle of lag $= \frac{18.84}{20} = 0.942$, which corresponds to an angle of 43.18 in.

In plotting the curves of alternating currents, or e.m.fs., it must be remembered that the maximum value at the crest of the wave is 1.415 times the effective value (see Fig. 138).

The quantity $\sqrt{R^2+(2\pi fL)^2}$ is called *the impedance* of the circuit and the current flow for a given impressed e.m.f., E, is

$$I = \frac{E}{\sqrt{R^2+(2\pi fL)^2}} \tag{50}$$

This formula shows that the alternating current follows Ohm's law, for the impedance is a combination of a resistance and a counter e.m.f.

Condenser.—If an e.m.f. be impressed at the terminals of a condenser, current will flow into it, and as the current is stored up, the condenser e.m.f. will rise, opposing the incoming current until a point is reached at which the condenser e.m.f. is equal and counter to the impressed e.m.f. When this condition is attained no further current passes into the condenser, and, consequently, the point of zero current flow corresponds to the maximum-condenser e.m.f.

Also, it is obvious that the rate of current flow into the condenser on charge is proportional to the difference between the impressed e.m.f. and the condenser e.m.f. which opposes the current. When an alternating e.m.f. is impressed on a condenser, current flows into it most rapidly when the condenser e.m.f. is zero, as it sets up no opposition to current flow, and the value of the impressed e.m.f. is such that at this point the greatest dfference exists between the impressed and the condenser e.m.fs. Hence, the condenser e.m.f. is zero at the instant when the current in the circuit is a maximum. When full charge and maximum-condenser e.m.f. are reached and current ceases to flow, the impressed e.m.f. begins to decrease and falls below that of the condenser, which latter then discharges into the circuit. The action is clearly shown by the curves in Fig. 142.

As in the case of the before-mentioned inductive circuit, the current flow is always in proportion to and in phase with that e.m.f. which is the resultant of all the e.m.fs. acting on the circuit. Calling the curve i,i,i,i the amplitude and phase of the current, V, V, V, V is the phase and, to some convenient scale, the

amplitude of the resultant e.m.f. When the current is zero—as at Z—the condenser is fully charged, its e.m.f. being equal to that of the impressed e.m.f. at this point. The difference between the two pressures being zero, the current flow is zero. Immediately on passing this point, the impressed e.m.f. falls below that of the condenser and the latter begins to discharge, thereby lowering its voltage; hence, the point of zero current flow is the point of maximum condenser e.m.f.

From W to Z the condenser is being charged. From Z to N it discharges. From W to Z the condenser e.m.f. increases, as shown by C,C,C,C, the curve of condenser e.m.f. Drawing C,C,C,C so that its maximum is coincident with zero current

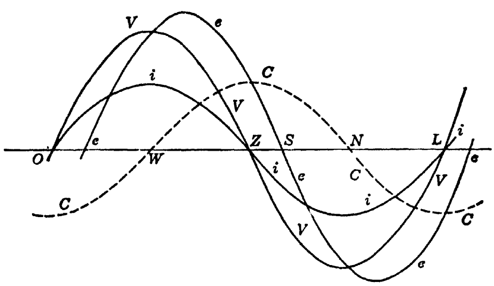


FIG. 142.—E.m.f. curves. Resistance and capacity.

flow, and its zero coincident with maximum current flow, it is evident that the condenser e.m.f. is one-forth period, or 90° *ahead* of the current flow.

The summation of the e.m.f. curves, V,V,V,V and C,C,C,C, gives curve e,e,e,e, which is the impressed e.m.f.

The addition of this curve makes the explanation somewhat clearer.

At W, e is greater than C by the maximum amount, and consequently, the greatest current will flow, as is shown by curve i. The difference between e,e,e,e and C,C,C,C constantly decreases and the current flow, therefore, diminishes as is indicated by curve i,i,i,i, until point Z is reached, at which e,e,e,e is equal to C,C,C,C, and the current flow is zero. Passing point Z, the impressed e.m.f. still further decreases and the condenser begins to discharge, the current now flowing in the opposite direction. As discharge proceeds the condenser voltage falls off, until at point N its e.m.f. is zero. Before point N is reached, however,

the impressed e.m.f. reaches zero—say at S. Up to the time of reaching zero, the imprcssed e.m.f. has opposed the condenser discharge, and the current flowing has been due to the net e.m.f., which is the difference between these two e.m.fs. When the impressed e.m.f. becomes zero the condenser e.m.f. is no longer opposed, and when the impressed e.m.f. passes through zero it acts with the condenser e.m.f., assisting the latter to send current through the circuit. When the condenser e.m.f. reaches zero, the impressed e.m.f. has risen to such a value that the maximum current flows into it, but opposite to the direction in the first half of the cycle, and the condenser begins to charge in an opposite direction, charge continuing until the point L is reached, when the current becomes zero, and the condenser e.m.f. a maximum. The cycle then is repeated as before.

From this it follows that (1), the impressed e.m.f., is the sum of the active or resultant e.m.f. and the condenser e.m.f.; (2) the condenser e.m.f. reaches its maximum value one-fourth period ahead of the resultant e.m.f., or, reckoned in terms of armature rotation, 90° (= ¼ revolution) ahead of the resultant e.m.f., and (3), that the resultant e.m.f., and consequently the current, is in advance of the impressed e.m.f., but behind the condenser e.m.f.

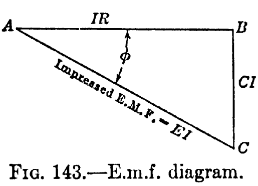


FIG. 143.—E.m.f. diagram.

Since the condenser e.m.f. is 90° ahead of the resultant e.m.f., a diagram similar to Fig. 141 may be used for computations.

In Fig. 143 the horizontal line, AB, represents, to scale, the effective value of the resultant voltage = IR. CI is the effective value of the condenser voltage, laid off downward, to show that it is in opposition to inductance, which latter being 90° behind the resultant e.m.f., is 180° behind the condenser e.m.f., and, therefore in exact opposition thereto.

ϕ is the angle of lead and its tangent is, obviously, $\frac{CI}{RI}$, or $\frac{C}{R}$.

The cosine of the angle ϕ, which is seen to be $\frac{R}{\sqrt{R^2 + C^2}}$, is the circuit "power factor," which term will be treated at some length later.

The value of the voltage set up at the terminals of a condenser, due to the passage of current into it, is computed as follows:

By definition, a capacity of 1 farad will allow the storage of 1 coulomb, with 1 volt impressed on the condenser terminals. The quantity stored varies as the maximum e.m.f. impressed. One coulomb, stored in a condenser of 1 farad capacity, is at 1 volt constant pressure, such as a continuous-current dynamo or a battery would deliver. A constant pressure is the same as the average of the voltage, taken over any length of time. The average of a sinusoidally varying pressure is 0.6366 the value of the maximum. The quantity of electricity stored in any condenser is proportional to the maximum voltage impressed on it. The ratio of the average to the maximum of an alternating voltage, (assuming a sine wave) is 1 to $\frac{1}{0.6366} = 1{:}1.57$, 0.6366 being the average of all the ordinates of a sine curve the maximum ordinate of which is 1. Therefore, for an *average* e.m.f. of 1 volt alternating, the coulombs stored = 1.57 coulombs.

Since a condenser is twice filled and twice emptied during one cycle, the quantity of electricity it receives on charge passes four times through the circuit, and for one cycle at 1 volt effective e.m.f., the quantity of electricity passing through a condenser of 1 farad capacity will be $4 \times 1.57 = 6.28$ coulombs, if the current follows the sine law. As 1 coulomb per second is 1 amp., 6.28 amp. will flow through the condenser if the frequency be one cycle per second. From which it is plain that

$$I = 6.28 \times f \times E \times J \tag{51}$$

When the relations of sine functions are investigated trigonometrically, the coefficient 6.28 in the foregoing formulæ appears as 2π, and the usual formula for condenser current is $I = 2\pi fJE$, from which

$$E = \frac{I}{2\pi fJ} \tag{52}$$

which is the *effective* e.m.f. required at the terminals of a condenser having a capacity J, to pass the effective current, I, through it.

The farad is much too large a unit for practical use and the microfarad, or one-millionth of a farad is generally used. Calling this Jm, formula (52) becomes

$$E = \frac{I \times 1{,}000{,}000}{2\pi fJm} \tag{53}$$

As an example, take the case of a circuit having in it a resistance = 8 ohms and a capacity = 50 microfarads. Frequency of impressed e.m.f., 100 cycles per second and effective voltage 100.

From the Fig. 143

$$EI = \sqrt{(IR)^2 + (CI)^2}, \text{ or } E = \sqrt{R^2 + C^2} \qquad (54)$$

C being the reactance of the condenser.

From equation (53) the voltage at the terminals of a condenser is $Ec = \frac{1{,}000{,}000}{2\pi fJm}$ for 1 amp. (effective) flowing through it.

Whence,

$$\sqrt{R^2 + \left(\frac{1{,}000{,}000}{2\pi fJm}\right)^2} = \sqrt{(8)^2 + \left(\frac{1{,}000{,}000}{6.28 \times 100 \times 50}\right)^2}$$

$= 32.82$ volts for each ampere flowing through the circuit.

Current $= \frac{100}{32.82} = 3.05$ amp. Tangent angle of lead $= \frac{\frac{1{,}000{,}000}{2\pi fJm}}{R}$ $= \frac{31.83}{8} = 3.98$, corresponding to an angle of 75° 54″.

Watts Output.—It is evident that the actual watts supplied to an alternating-current circuit are the product of the resultant, or active, e.m.f., multiplied by the current flow, and not the impressed e.m.f. × current, except in those cases where the impressed e.m.f. coincides in phase position and magnitude with the resultant e.m.f.

The impressed e.m.f. is greater than the resultant e.m.f. by an amount sufficient to pass current into a condenser or through an inductance; but this excess does not represent energy supplied continuously. Inductances and condensers merely store up energy, and the excess given up during one portion of the cycle is returned to the circuit at some other portion of the cycle.

It is customary to speak of "wattless current" in circuits where there is a phase displacement, when, in reality, there is no such thing possible in practice, as current is wattless only when the resultant e.m.f. of the circuit is zero. An alternating e.m.f. impressed across the terminals of an inductance would result in the flow of wattless current if the entire circuit were without resistance. Since there is resistance in every circuit, there can be no wattless current; but if the inductive e.m.f. be very great and the resistance very small, nearly all of the impressed e.m.f. will be used up in overcoming the opposing inductive e.m.f.,

and the net useful, or resultant, e.m.f. is so small that a large current flow is necessary to produce any appreciable output in useful watts. As an example, if there be an inductance in a circuit which has an impressed e.m.f. of 100 volts, and the resultant, or active, e.m.f. is 90 volts, to deliver 10 kw. will require 111.1 amp. If the inductance were not present, the impressed e.m.f. would also be the active e.m.f. and to deliver 10 kw. would require 100 amp. The difference between these two, or 11.1 amp., is the increase in current required to deliver a given output due to the decrease in net useful voltage. The *apparent* watts delivered are 100 × 111.1 = 11.1 kw.; but this amount of energy is neither generated nor supplied, and since there appears to be more current than is necessary to produce the output, it has become customary to term part of the current "wattless," a designation which has no foundation in fact. It is convenient, however, in certain alternating-current problems, to consider the impressed e.m.f. as the net useful voltage and to separate the current into two components, one being the useful component in phase with the e.m.f., the other at an angle of 90° to the e.m.f. Thus, in Fig. 144, if 100 volts are impressed on the circuit and the ampere-meter shows 111.1 amp. passing through it, while the delivered power is actually 10 kw., it may be assumed that 100 amp. of the current are in phase with the e.m.f., while at 90° to this useful, or energy, component there is a "wattless" component, equal to $\sqrt{(111.1)^2 - (100)^2} = 48.3$ amp. are at 90° to the e.m.f., and this 48.3 amp. is the wattless component of the current flowing. All this is a mathematical fiction which has no physical existence and is misleading unless it be recognized as simply an artificial method of computation.

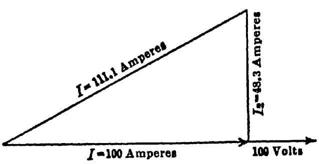


FIG. 144.—Current diagram.

Referring to Figs. 141 and 143, it is plain that the active or resultant voltage which does useful work in the circuit and represented by the horizontal line, IR, is equal to the impressed e.m.f., multiplied by the cosine of the angle of lead or lag—the impressed e.m.f. being equal to the length of the hypothenuse of the right triangle.

In the example before given in which the effect of a condenser

having a capacity of 50 microfarads, included in series with a resistance of 80 ohms, is discussed, the current at 100 volts impressed e.m.f., and frequency of 100 cycles per second, was found to be 3.05 amp., and the angle of lead 75° 54″. The cosine of 75° 54″ = 0.2438.

The actual energy, then, put into the circuit is 3.05 × 100 × 0.2438 = 74.36 watts.

The cosine of the so-called angle of lead or lag is known as the power factor. This quantity multiplied by the impressed e.m.f. gives the resultant or active e.m.f.

This same result may be obtained by combining the impressed and reactance voltages. Since $I = 3.05$ amp. reactance voltage = $\frac{1{,}000{,}000 \times 3.05}{\omega J m} = 94.25$ volts. Resultant voltage = $\sqrt{E^2 - C^2} = \sqrt{(100)^2 - (94.25)^2} = 24.4$ volts. Watts = 24.4 × 3.05 = 74.4 watts.

The foregoing shows that large currents may often be required to supply a small amount of energy, because the resultant voltage is small where the reactances in the circuit are large. This current, however, is not hypothetical nor imaginary, and conductors sufficiently large to carry it must be provided for its transmission. The power loss in a circuit is always equal to the square of the current flowing multiplied by the resistance of the circuit, and this so-called "wattless" current is no exception to the rule.

If, in the last example, with a pressure of 100 volts, 2 ohms were the resistance of the line, and 6 ohms the resistance of the receivers—say incandescent lamps—the line loss would be $(3.05)^2 \times 2 = 18.65$ watts, while the total energy supplied to the circuit is 74.46 watts, the percentage loss being 25 per cent. If there were no capacity in the circuit and the total ohmic resistance were 32.83 ohms, or 2 ohms resistance in the line, and 30.83 ohms, the resistance of the receivers, the current would be 3.05 mp. as before, but the watts delivered to the circuit = 3.05 × 100 = 305, and the loss 18.65 watts, as before, the percentage loss in this case being 6.25 per cent. From which it follows that the energy loss in conductors is proportional always to the square of the current, regardless of phase, although the watts delivered to the terminals of a receiver are proportional to the current, impressed voltage and power factor. Under one condition, the transmission of a certain amount of energy will result in a given loss. By changing the reactance in the circuit the energy may be

reduced although the current may be increased, producing a correspondingly greater line loss.

Combined Inductance and Condensance.—From the previous considerations it is plain that inductance and capacity in the same circuit tend to neutralize each other, and in certain instances may completely do so.

If the resistance, $R = 10$ ohms, the inductance, $L = 0.05$ henry, the capacity, $Jm = 8.33$ microfarads, $f = 60$ cycles per second, and impressed $E = 100$ volts, their relationships are shown by the diagram, Fig. 145.

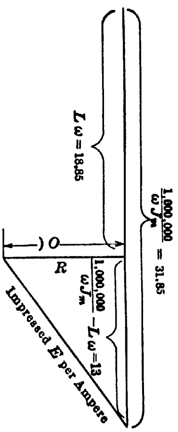


FIG. 145.—Relation of inductance and condensance.

Inductance reactance $= 2\pi fL = 18.85$ volts per amp.

Capacity reactance $= \frac{1,000,000}{2\pi fJm} = 31.85$ volts per amp.

• The reactance e.m.f. in the circuit then is $31.85 - 18.85 = 13$ volts, while the resistance e.m.f. is 10 volts for each ampere flowing. The impedance, then, of the circuit $= \sqrt{10^2 + 13^2} = 16.4$. $I = \frac{100}{16.4} = 6.1$ amp.

The tangent of the angle—which is the angle of lead in this case as the capacity reactance is the greater—is $\frac{13}{10} = 1.3$, corresponding to 48° 30″. Cosine 48° 30″ = 0.6626. The resultant voltage, therefore, is $0.6626 \times 100 = 66.26$ volts. Watts put into circuit $= 66.26 \times 6.1 = 404$ watts. Apparent watts = 610 watts.

The general formula for current flow in an alternating-current circuit is

$$I = \frac{E}{\sqrt{R^2 + \left(2\pi fL - \frac{1,000,000}{2\pi fJm}\right)^2}} \qquad (55)$$

Also, formula for tangent of angle lag or lead is

$$\text{Tan } \phi = \frac{2\pi fL - \frac{1,000,000}{2\pi fJm}}{R} \qquad (56)$$

the greater of the two quantities in the numerator showing whether the current "leads" or "lags behind" the impressed e.m.f.

Equation (55) shows that when the condenser and inductance reactances are equal, the formula reduces to $I = \frac{E}{R}$, showing that the summation of the three e.m.fs. acting is equal to the impressed e.m.f., and the resistance alone opposes the flow of current, the two reactances neutralizing each other. This is also shown in Fig. 146, where it will be seen that the ordinates of L, L, L, L are at every instant exactly equal and opposite to those of c, c, c, c, L, L, L, L being plotted 90° or one-fourth cycle behind the current, and c, c, c, c, being plotted one-fourth cycle ahead of the current curve, i, i, i, i.

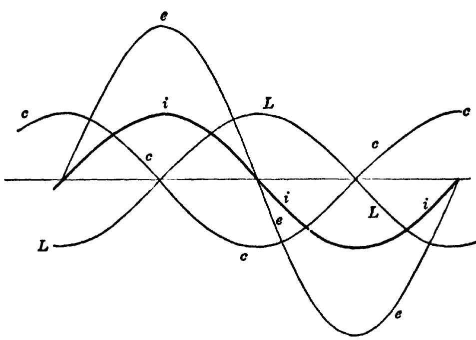


FIG. 146.—Relation of induction and condensance in circuit.

The resultant e.m.f. is, of course, equal to the impressed e.m.f. $= RI$.

With a given inductance and capacity, there is only one frequency at which they will neutralize, since their reactance voltages must be equal, and any increase in frequency will reduce the voltage of the condenser reactance, while it will increase the voltage of the inductance, and the reverse is true for a decrease in frequency, as is obvious from equations (50) and (51). This neutralization is, however, independent of resistance, current flow, or impressed e.m.f.

Complete neutralization of reactance is called *resonance.*

Since, for resonance, $2\pi f L = \frac{1{,}000{,}000}{2\pi f J m}$, the frequency at which resonance will occur is:

$$f = \frac{1}{2\pi}\sqrt{\frac{1{,}000{,}000}{LJm}} \tag{57}$$

As an example, assume a circuit in which $L = 0.44$ henry and $Jm = 16$ microfarads:

$$f = \frac{1}{6.28}\sqrt{\frac{1{,}000{,}000}{0.44 \times 16}} = 60 \text{ cycles per second.}$$

When inductance and capacity are both present in series relationship, voltages much greater than the impressed may manifest themselves locally at the terminals of the two reactances. For instance, in the previous example with conditions as shown in Fig. 145, the impressed e.m.f. = 100 volts, $I = 6.1$ amp., $f = 60$.

e.m.f. at inductance terminals $= 6.28 \times 60 \times 0.05 \times 6.1 =$ 115 volts.

e.m.f. at condenser terminals $= \dfrac{1{,}000{,}000 \times 6.1}{6.28 \times 100 \times 50} = 194$ volts.

In the case of resonance, the local voltages rise much higher than where partial neutralization only takes place, because the current flow is greatest when resonance occurs, and I is one of the factors that cause the voltage rise. In the case of the circuit in which $L = 0.44$ henry, $Jm = 16$ microfarads, $R = 5$ ohms, and $f = 60$; if the impressed e.m.f. be taken at 250 volts, $I = \dfrac{E}{R}$ $= 50$ amp. When a condensance and an inductance are in resonance, the local voltages across the terminals of the condenser and inductance are always equal to each other. Voltage at terminals of inductance $= 6.28 \times f \times L \times I = 8290$ volts. This is equal to the potential set up at the condenser terminals =

$$\frac{I \times 1{,}000{,}000}{6.28 \times f \times Jm} = \frac{50 \times 1{,}000{,}000}{6.28 \times 60 \times 16} = 8290 \text{ volts.}$$

Currents which are not in phase with each other may be combined just as are e.m.fs. In the case of two parallel branches of a circuit, as shown in Fig. 147, the current in branch A will lag behind the impressed e.m.f., and that in branch B will be in advance of the impressed e.m.f., it being understood that the terms "lag" and "lead" are used in the sense before explained.

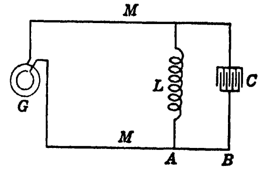


FIG. 147.—Diagram of circuit with inductance and condensance.

The current through the mains MM is the algebraic sum of the currents in A and B, if the *instantaneous* values be taken.

Figure 148 shows the curves of impressed e.m.f. (e,e,e,e), current in A, (A,A,A,A), current in B, (B,B,B,B) and the algebraic sum (i,i,i,i), which is the resultant current through MM.

It is inconvenient to plot these curves accurately to scale and the method of combining forces graphically is best suited to the investigation of such circuits.

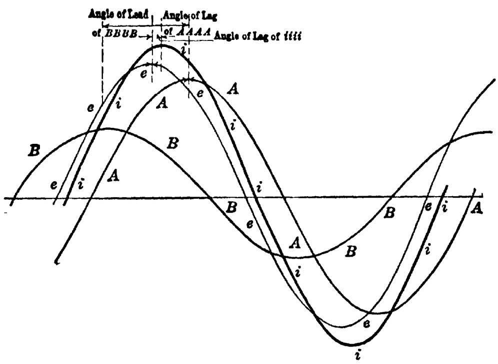


FIG. 148.—E.m.f., current, and resultant curves.

If in Fig. 149 the horizontal line, OX, represents the impressed e.m.f., the current through A is equal to I_1.

$$I_1 = \frac{E}{\sqrt{R^2 + (\omega L)^2}}$$

in which $\omega = 2\pi f$.

The tangent of the angle of lag $= \dfrac{L\omega}{R}$.

Lay off OI_1 equal to I_1, and at an angle ϕ the tangent of which is $\dfrac{L\omega}{R}$ behind the e.m.f.

Also the current through B is

$$I_2 = \frac{E}{\sqrt{R^2 + \left(\dfrac{1{,}000{,}000}{\omega Jm}\right)^2}}$$

and the tangent of the angle of lag, is $\dfrac{\dfrac{1{,}000{,}000.}{\omega Jm}}{R}$. Lay off OI_2 equal to I_2 and at the angle θ, ahead of the e.m.f. The resultant current is the diagonal of the parallelogram made on

OI_1 and OI_2. As may be seen, it is in this case slightly ahead of the impressed e.m.f. by an angle $= a$.

As an example, take a circuit in which branch A has a resistance of 5 ohms and an inductance of 0.02 henry.

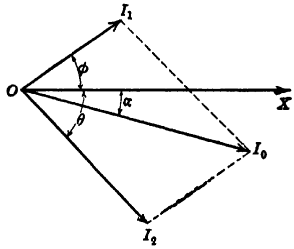


FIG. 149.—Current diagram.

Branch B has a capacity of 50 microfarads and 8 ohms.

Assume an impressed e.m.f. of 100 volts and a frequency $= f$ of 100 cycles per second. $2\pi fL = 6.28 \times 100 \times 0.02 = 12.56$ volts.

Impedance of branch $A = \sqrt{(5)^2 + (12.56)^2} = 13.5$. Current through branch $A = \frac{100}{13.5} = 7.42$ amp. The resultant e.m.f. and the current lag behind the impressed e.m.f. by an angle, the tangent of which is $\frac{L\omega}{R} = \frac{12.56}{5} = 2.513$, which angle is 68° 18″.

The impedance of the condenser circuit =

$$\sqrt{R^2 + \left(\frac{1{,}000{,}000}{\omega Jm}\right)^2} = \sqrt{(8)^2 + \left(\frac{1{,}000{,}000}{50 \times 628}\right)^2}$$

$= 32.82$. Current $= \frac{100}{32.82} = 3.05$ amp.

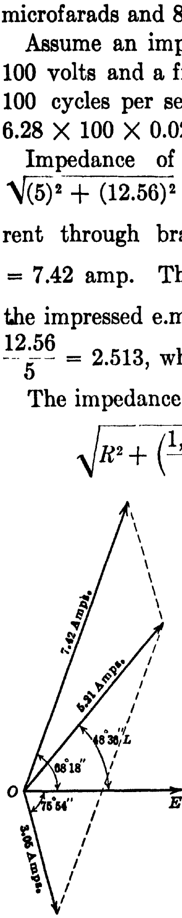


FIG. 150.—Current diagram.

Tangent angle of lead $= \frac{\frac{1{,}000{,}000}{\omega Jm}}{R} = \frac{31.83}{8} = 3.98$, corresponding to an angle of 75° 54″. Combining these two currents in their proper phase relation, the sum is the current through the main circuit. This addition is done as shown in Fig. 150 in which OE is the reference line representing the impressed e.m.f. From O at an angle of 68° 18″ *upward* lay off to any convenient scale 7.42 amp. At an angle of 75° 54″ *downward* lay off to the same scale 3.05 amp. Complete the parallelogram as indicated by the dotted lines. The diagonal from O gives the value of the resultant current through the main circuit at 5.24 amp., and shows that this current is 48° 36″ behind the im-

pressed e.m.f. Thus, it will be seen that in this particular case the combined currents of the two branches is less than that in the single branch, *A*, and the addition of branch *B*, which affords a second path for current flow from the circuit in which the single path, *A*, exists, actually reduces the total current flow through the circuit.

If the two branches, *A* and *B*, had no resistance in them, and the capacity and inductance were so related that, for a given frequency, the currents in the two branches would be equal, then the current through the main circuit would be zero. The currents being equal and opposite would neutralize. The physical conception of this condition is that of current flowing into the condenser, charging it while the energy previously stored in the inductance discharges. This discharge sets up an e.m.f. opposing the impressed e.m.f. and also furnishes the current to supply the charge in the condenser. On reversal of the impressed e.m.f. the condenser discharges into the inductance, at the same time opposing the impressed e.m.f. Thus, current will flow in the local circuit between *A* and *B*, but none will flow in the main circuit, as the impressed e.m.f. is always opposed by an equal and opposite e.m.f. The current which surges back and forth between *A* and *B* is a so-called "wattless current," because its net effect in doing work is zero. During the transfer of energy from the inductance to the condenser, or *vice versa*, an amount of energy is transferred proportional to the current flow, but is restored when discharge takes place, sending the current in the opposite direction and back into the reactance from which it was first taken.

Multiphase Currents.—All the preceding discussion applies to single-phase alternating currents. In hydro-electric developments and power transmission, three-phase currents are almost universally used though two-phase systems have been occasionally installed.

If an electric generator is provided with two sets of armature coils instead of one, and the position of the two on the armature is such that the maximum electromotive force of one set occurs at the instant that the e.m.f. of the other set is zero, and each set of coils has its independent circuit, a two-phase current will be generated by the machine.

Figure 151 is a diagram of the two e.m.fs. and shows their mutual time relationship. The phases are said to be at 90° to each other.

Obviously, the power in a two-phase circuit is equal to the sum of the separate amounts in each pair of conductors, since a two-phase system is simply two single phases, rigidly fixed in their time relation to each other. If the power is equally divided between the phases the current in any wire is

$$I = \frac{1000 \text{ kw.}}{2E} \text{ amp. for non-inductive load.}$$

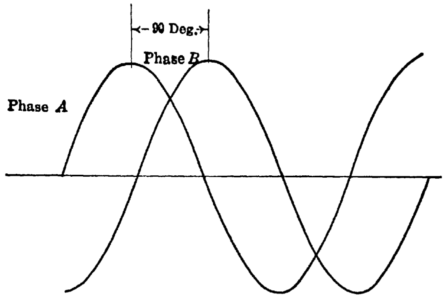


FIG. 151.—Two-phase currents.

For inductive load

$$I_i = \frac{1000 \text{ kv.a.}}{2E} \text{ amp.}$$

$$\text{kv.a.} = \frac{\text{volts} \times \text{amperes}}{1000} = \frac{\text{kw.}}{\phi}$$

$$\phi = \text{power factor.}$$

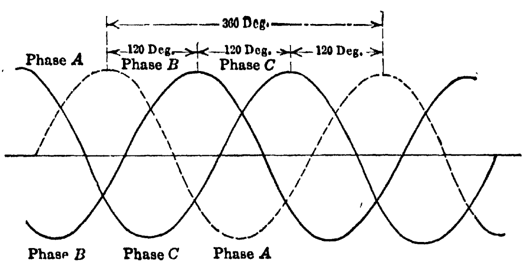


FIG. 152.—Three-phase currents.

If an armature has three windings placed on it, so that the middle points of the coils are spaced 120° (electrical) apart three separate electromotive forces will be generated and the maximum value of each of the three waves will occur at a different instant, and 120° apart.

Figure 152 shows e.m.fs. and their time relationship.

The current may be taken off by three pairs of wires, but this is unnecessary. It is a property of the three-phase system that the sum of all the currents in the different phases, at any instant, is zero. Hence, three wires only are required to transmit the current.

Due to the use of three wires instead of six, the current in each wire is greater than one-third that which it would be for an equal amount of energy from a single-phase system. The current in each wire is

$$I = \frac{1000 \text{ kw.}}{\sqrt{3}E} \text{ amp. for non-inductive load.}$$

or

$$I_i = \frac{1000 \text{ kv.a.}}{\sqrt{3}E} = \frac{\text{kw.}}{1.732\phi E} \text{ amp.}$$

for inductive load.

The total power in a three-phase circuit is

$$\text{kw.} = 1.732EI\phi$$

and

$$\text{kv.a.} = 1.732EI.$$

In every case, E is the voltage measured between any two wires of the circuit.

There is also the so-called "voltage to neutral" which is the voltage between any one of the three wires and a fourth wire,

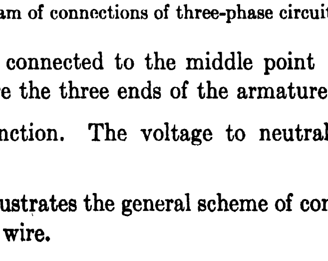


FIG. 153.—Diagram of connections of three-phase circuit with neutral wire.

which latter is connected to the middle point in the generator armature, where the three ends of the armature coils are united in common junction. The voltage to neutral is $\frac{E}{1.732}$ for 3-phase circuits.

Figure 153 illustrates the general scheme of connections including the neutral wire.

A neutral wire is seldom run as a complete line over the whole length of transmission, though the earth is frequently used as the neutral conductor, the wire from the middle point of the generator—or, what amounts to the same thing, from the middle point of transformers (star-connected)—being connected to the earth. No working circuits are taken off between any line wire and the neutral, but the voltage between the neutral and any line wire is a convenient quantity to use in making transmission-line calculations as will be seen later.

CHAPTER X

CALCULATION OF TRANSMISSION LINES

A transmission line possesses resistance, inductance and capacity. Of these, none but the resistance affects the current flow and voltage drop when direct, or uni-directional, currents are transmitted. When alternating currents flow over line, however, all three of these factors influence the voltage and current flow.

A single-phase line may be represented by the diagram, Fig. 154. The resistance and inductance are in series, while the capacity has the same effect as a shunt along the entire length of the line.

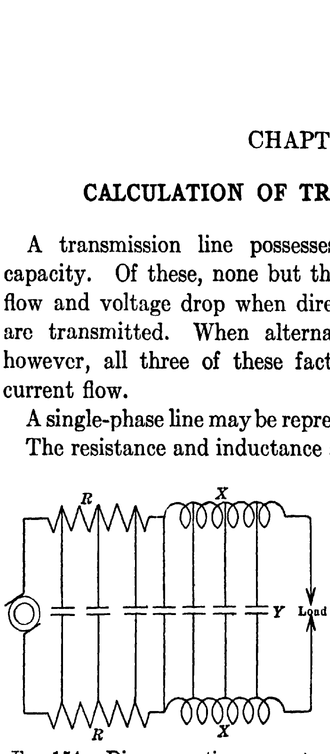


FIG. 154.—Diagrammatic representative of a transmission line.

Mr. H. B. Dwight, B. Sc., has devised a chart from which the various constants of a transmission line may be taken directly,[1] with great saving of labor in computation. A copy of this chart is herewith produced by courtesy of Mr. Dwight and the Van Nostrand Co. (see Fig. 155 on inside of back cover).

Its use is very simple. If a straight edge be placed so that it passes through the point near the left-hand side of the chart, representing the distance of separation of the wires of the line, and also passing through the point on the right-hand side of the chart, representing the resistance per mile of one of the conductors of the line, the regulation factor F can be read off along the line joining these two points and at its intersection with an intermediate vertical line corresponding with the power factor

[1] "Transmission Line Formulas," by HERBERT BRISTOL DWIGHT.

of the load. The regulation and voltage drop can then be computed from simple formulæ, with the slide rule.

Obviously, the converse of this first operation is equally easy to solve by the chart. If the load, line length, power factor of load, voltage at load end, frequency, and character of material of the transmission line be given, and the required regulation be specified, the resistance of the line and the size of wire necessary, can be found, directly, from the chart. Care must be taken in placing the straight edge on the point where the spacing of the lines is given, to select the point corresponding to the metal used (copper or aluminum) and in that group belonging to the proper frequency. Also, the "regulation factor," F, is to be read off on that scale corresponding to the power factor of the load. The necessary formulæ for all computations connected with the chart are given in the plate.

As an example take the following conditions.

Frequency = 60 cycles.

Separation of wires = 7 ft.

Conductors of aluminum.

These three conditions fix the location of the left-hand point on the chart.

Required, the regulation, line drop and voltage at generator end when delivering 5000 kw. at the load end: power factor 0.85; size of wire No. 000; length of line (L) = 60 miles, and voltage at load end 66,000 volts, measured between wires.

Placing the straight edge on the proper left-hand point in the 60-cycle group and on the right-hand point marked "No. 000 Alum," it is found that the line between these two points intersects the vertical line marked "85" at the point having a value 0.865 which is the value of F.

$$\text{Per cent. regulation} = \frac{L \times F \times \text{kv.a. } 10^5}{E^2}.$$

L = length of line in miles.

F = regulation factor.

E = volts at load end of line between wires.

$$\text{kv.a.} = \frac{5000}{0.85} = 5880$$

$$E^2 = (66{,}000)^2 = 4356 \times 10^6$$

$$\text{Per cent. regulation} = \frac{60 \times 0.865 \times 5880 \times 10^5}{4356 \times 10^6} = 7 \text{ per cent.}$$

Per cent. line drop = per cent. regulation $- \quad 100K\left(\frac{L}{1000}\right)^2$

K is a constant = 2.16 for 60 cycles and = 0.375 for 25 cycles.

Per cent. line drop $= 7 - 100 \times 2.16\left[\frac{60}{1000}\right]^2 = 7 - 0.777 =$ 6.223 per cent. of the delivered voltage.

Volts line drop = 6.223 per cent. of 66,000 = 4107 volts.

If the same conditions as just preceding be assumed, except that the regulation is to be within 12½ per cent., and the size of the conductor is to be determined, it is first necessary to compute F,

$$F = \frac{(\text{per cent. reg.}) \times E^2}{\text{kv.a.} \times L \times 10^5}.$$

$$\text{For this case, } F = \frac{12.5\ (66{,}000)^2}{5880 \times 60 \times 10^5} = 1.54.$$

Laying a straight edge from the 60-cycle, 7-ft. separation point, on the line marked "Aluminum," to the point having a value of 1.54 on the intermediate vertical line marked "85," it is found that the straight edge intersects the ohm's resistance line on the right-hand edge of the chart, at a point which gives the resistance, per mile, of the conductor as 1.30 ohms, which for aluminum, lies between No. 1 and No. 2 B. & S. gauge.

If size No. 1 be adopted, the actual regulation can be immediately determined from a simple proportion, thus:

Factor F = 1.54 gives a regulation of 12½ per cent.

Factor (from chart) for No. 1 aluminum is 1.35.

$$\text{Regulation} = \frac{12.5 \times 1.35}{1.54} = 11 \text{ per cent.}$$

This chart is sufficiently accurate for lines up to 200 miles in length.

Short Branches. Current-carrying Capacity.—When short connecting lines are tapped off the main transmission line, or in the case of interior high-pressure bare wires, any computation to fix the size of wire on the basis of voltage drop will probably give too small a cross-section. The current density will be too great and the temperature attained by the wire too high.

It is desirable to limit the temperature rise in bare wires to 150°C. above the surrounding air. Any higher temperature may expand the wires and ties so that the wires will sag and the ties loosen.

The formula for the carrying capacity of wires in still air is

$$I = 800\sqrt{\frac{Td^3}{r}} \tag{60}$$

T = temperature rise, in degrees C.

d = diameter of wire, in inches.

r = resistance of metal in the conductor, *per mil foot*, at final temperature.

For a maximum rise of 150°C. this formula reduces to the following:

For copper wires

$$I = 2400d^{3/2} \tag{61}$$

For aluminum wires

$$I = 2080d^{3/2} \tag{62}$$

If the wires are in air currents, and convection is continuous, the current may be increased 25 per cent. above the values given by the formula.

Transmission-line Formulæ.—The following formulæ for transmission lines cover every condition that will be found in practice. Three are given. The first set is for short lines—40 miles or less—and neglects the capacity effects.

The second set comprises the approximate formulæ of Dwight[1] which are sufficiently accurate for every practical purpose, giving results within ½ per cent. of the theoretically exact values.

The last set of formulæ involves the use of a convergent series and requires the computations to be made with complex quantities. The calculations are prolonged and tedious, and the greater accuracy, as compared with the formulæ of Dwight, is of no practical importance.

The last formulæ are here given for the use of engineers who prefer to use complex quantities, or who may desire to check their computations by two radically different methods.

In reality, the final formulæ all take the same form. The real differences lie in the methods of determining the constants that are used in the general formulæ.

The factors to be computed are designated A, B, C, and D. These are found by any method selected, using as known quantities the following:

[1] See "Transmission Line Formulas," by HERBERT BRISTOL DWIGHT, B. Sc.

Kw. or kv.a., at load end.

E_L = volts at load end of line, between wires.

V_L = volts at load end of line, between any wire and the neutral.

r = resistance of one wire of the line, per mile.

$R = rL$ = total resistance of one wire of the line.

x = reactance of one wire of the line, per mile.

$X = xL$ = total reactance of one wire of the line.

b = capacity susceptance of one wire of the line, per mile.

$Y = bL$ = total capacity susceptance of one wire of the line.

S = distance of separation of wires, in feet.

Cos Φ_L = power factor of the load.

$\text{Sin } \Phi_L = \sqrt{1 - \cos^2 \Phi_L}$

$P = I_L \cos \Phi_L$

$Q = I_L \sin \Phi_L$

f = frequency, in cycles per second.

The problem is, usually, to determine the values of:

E_G = voltage between wires, at the generator end of the line at full load.

E_{0G} = voltage at no load, at generator end.

r, or R, the resistance of the line (from a preliminary calculation).

I_L = current at load end per wire at full load.

I_G = current at the generator end per wire on full load.

I_{0G} = current at the generator at no load (*i.e.*, line-charging current).

Kv.a. and kw. at generator end at full load.

Kv.a. and kw. at generator end at no load.

Kw. loss in line at full load.

Power factor = cos Φ_G at generator end.

Regulation at receiver end for constant voltage of supply.

For any conditions, or any formula used, the following fundamental relations hold:

$$\frac{\text{Kw.}}{\text{Cos } \Phi} = \text{kv.a.}$$

$$V = \frac{E}{\sqrt{3}}, \text{ for three-phase circuits.} \qquad (63)$$

$$V = \frac{E}{2}, \text{ for two-phase or single-phase circuits.} \qquad (64)$$

$$I = \text{current per wire} = \frac{\text{kv.a.} \times 1000}{\sqrt{3} \times E} = \frac{\text{kv.a.} \times 1000}{3V}, \text{ for three-phase circuits.} \qquad (65)$$

$$I = \frac{\text{kv.a.} \times 1000}{E}, \text{ for single-phase circuits.} \tag{66}$$

$$I = \frac{\text{kv.a.} \times 1000}{2E}, \text{ for two-phase circuits.} \tag{67}$$

Energy loss in line $= I^2R$, per wire, in which R is total resistance of one wire of the line. Total energy loss $= nI^2R$, in which n = number of wires. Note that when the charging current of a line is appreciably great, I is variable along the length of the circuit, and the actual energy loss cannot be accurately determined from the I^2R formula. It can, however, be approximated for preliminary computations in this way.

In designing lines, it is usually customary to fix the allowable energy loss, or regulation required, as the fundamental factor. Next, the proper voltage is adopted, which is determined from the commercial conditions, as is set forth elsewhere.

The quantity of energy to be transmitted is known, together with the power factor of the load.

The distance of separation of the wires of the line is usually a matter of judgment of the designer, modified in high-tension work by the corona effect, as discussed in another part of this chapter.

Having these data the first computation is that of the approximate values of the current and size of the wire.

$$I_L = \frac{\text{kv.a.} \times 1000}{3V_L}, \text{ for three-phase circuit.} \tag{68}$$

Loss, per wire, for three-phase circuit = one-third total loss.

If p = percentage of total delivered energy that will be lost in the line on full load,

$$e = \frac{\text{Kw.} \times p}{3 \times 100}. \tag{69}$$

e = energy loss in each wire,

$$R = \frac{e}{I_L^2} \text{ (approximately).} \tag{70}$$

$\frac{R}{L} = r$, r being resistance, per mile, from which the size of the wire may be taken from Tables 20 and 21.

Having now the approximate size of the wire and its distance of separation, x, the reactance in ohms per mile, and b, the capacity susceptance, per mile, may be taken from the tables (see Tables 22 to 27). Multiplying each of these tabular values

by the length of the line, in miles, the result is X $(= xL)$ and Y $(= bL)$ respectively.

Factors A, B, C and D and A_0, B_0, C_0 and D_0 may now be computed by any of the formulæ later given.

Factors A, B, C and D are for full-load, while A_0, B_0, C_0 and D_0 are for no-load conditions. After these are found, the unknown quantities are calculated from the following general formulæ.

Full load | No load

Voltage at generator end of the line

$V_G = \sqrt{A^2 + B^2}$ (71) $\qquad V_{0G} = \sqrt{A_0^2 + B_0^2}$ (72)

Current, per wire, at the generator end

$I_G = \sqrt{C^2 + D^2}$ (73) $\qquad I_{0G} = \sqrt{C_0^2 + D_0^2}$. (74)

The computations will be simplified if instead of $\sqrt{x^2 + y^2}$, the approximation, $x + \frac{y^2}{2x}$ be used in numerical work when y is very small as compared with x.

Thus, $$V_G = A + \frac{B^2}{2A}.$$

Kv.a. at generator end.

Kv.a.$_G = 3V_G I_G$. (75) $\qquad$ Kv.a.$_{0G} = 3V_{0G} \times I_{0G}$. (76)

Kw. at generator end.

$$\text{Kw.}_G = \frac{AC + BD}{1000} \times 3. \quad (77) \qquad \text{Kw.}_{0G} = \frac{A_0C_0 + B_0D_0}{1000} \times 3. \quad (78)$$

Kw. loss in line, per wire.

$$e = \frac{\text{KW}_G}{3} - \frac{V_L I_L \cos\phi}{1000}. \quad (79)$$

Total loss for three-phase circuit = $3e$, and for two-phase = $4e$.

Regulation at load end for constant voltage at generator end =

$$V_L\left(\frac{V_G}{V_{0G}} - 1\right) \text{ volts.} \quad (80)$$

$$\text{Cos } \phi_G = \frac{\text{kw.}_G}{3V_G I_G}. \quad (81)$$

When the conditions are given at the supply, or generator end of the line, the quantities to be determined are, F, S, M, and N and:

$$V_L = \sqrt{F^2 + S^2} = F + \frac{S^2}{2F}. \quad (82)$$

$$\text{Kv.a.}_L = \left(F + \frac{G^2}{2F}\right)\frac{\sqrt{M^2 + N^2}}{1000}. \quad (83)$$

$$\text{Kw.}_L = 3 \times \left(\frac{FM + SN}{1000}\right). \tag{84}$$

$$\text{Cos } \phi_L = \frac{\text{kw.}_L}{\text{kv.a.}_L}. \tag{85}$$

After determining these values, the succeeding computations may be made from the formulæ 71 to 81, the formulæ 82 to 85 giving sufficient data to transfer the problem to the load end of the line.

Short Lines.—Considering now the computations of short lines—that is, 50 miles or less—and neglecting the capacity, the following are the values for A and B.

$$A = V \cos \phi + RI,$$
$$B = V \sin \phi + XI,$$

so that

$$V_G = \sqrt{A^2 + B^2} = \sqrt{(V \cos \phi + RI)^2 + (V \sin \phi + XI)^2}. \tag{86}$$

This is clear from the graphical construction shown in Fig. 156, which is the diagram showing the relationship between the various electromotive forces.

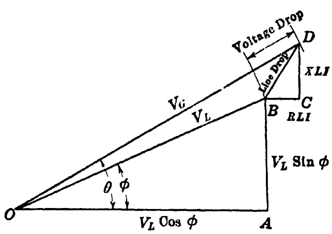


FIG. 156.—Composition of electromotive forces.

OA represents, to some adopted scale, the magnitude of the delivered voltage between one wire and the neutral in phase with the current, and is taken as the reference line. Its numerical value is $V_L \cos \phi$.

AB represents, to the same scale, the magnitude of the reactance voltage of the load, which is, numerically, equal to $V_L \sin \phi$. Its direction is at right angles to the in-phase voltage.

$OB = V_L$ is the vector resultant of the two electromotive forces $V \cos \phi$ and $V \sin \phi$. Its numerical value is

$$V_L = \sqrt{(V \cos \phi)^2 + (V \sin \phi)^2}. \tag{87}$$

BC is the ohmic drop of the current in *one* conductor and numerically equal to $rLI = RI$. Its direction is, obviously, the same as that of the in-phase voltage, and it is added to the delivered voltage E at the point B. CD is the reactance drop in one wire of the circuit. Its numerical value is $xLI = XI$ and

its direction is at right angles to that of the resistance drop. It being positive, its direction is upward from the reference line OA.

BD is the voltage required to send the current through one conductor, this line representing the vectorical sum of the resistance and reactance drops. The tangent of the angle of lag in the line is $\frac{x}{r}$ and the line drop is numerically equal to

$$\delta = \sqrt{(RI)^2 + (XI)^2}. \tag{88}$$

The generator voltage (line to neutral) is the vectorial sum of the line voltage and the delivered voltage, indicated by the line OD, or V_G, and has the numerical value as given in the equation (86).

The *voltage drop* is the numerical—not the vector—difference between the delivered and the generator voltages $= V_G - V_L$ volts, per wire.

From the diagram, it is clear that the voltage drop is not equal to the line drop, δ, except in the one case where the angle of lag of the line is exactly equal to the angle of the lag of the load. Hence, the delivered voltage, added to the line voltage, will give a sum in excess of the actual generator voltage required, except for this one condition.

Since capacity is neglected, the current is constant throughout the length of the line and $I_G = I_L$.

The power loss is for any single conductor $= RI^2$.

The percentage power loss is

$$p = \frac{100 \times I^2R}{V_L \cos \phi_L I} = \frac{100RI}{V_L \cos \phi_L} \text{ watts.} \tag{89}$$

$$R = \frac{pV_L \cos \phi_L}{100 \times I} \text{ ohms.} \tag{90}$$

The percentage voltage loss is

$$d = \frac{100(V_G - V_L)}{V_L}. \tag{91}$$

The power factor at the generator end is

$$\cos \phi_G = \left(\frac{100 + p}{100 + d}\right) \cos \phi_L.$$

As an example of the use of these formulæ, consider the llowing conditions:

Distance of transmission, 40 miles.

A three-phase, 60-cycle plant is to deliver 6000 kw. Wire spacing 6 ft., arranged in equilateral triangular form. Voltage at the load end to be 50,000 between wires, at full load.

Power factor of load, 85 per cent. = 0.85.

Maximum energy loss at full load = 8 per cent.

$V_L = \dfrac{50{,}000}{\sqrt{3}} = 28{,}870$ volts between any wire and the neutral.

$$I_L = \frac{6{,}000 \times 1{,}000}{3 \times 28{,}870 \times 0.85} = 81.5 \text{ amp. per wire.}$$

$V_L \cos \phi = 28{,}870 \times 0.85 = 24{,}540$ volts.

$\sin \phi = \sqrt{1 - (0.85)^2} = 0.526.$

$V_L \sin \phi = 28{,}870 \times 0.526 = 15{,}191.$

$R = \dfrac{8 \times 24{,}540}{100 \times 81.5} = 24.08$ ohms.

$r = \dfrac{R}{L} = \dfrac{24.08}{40} = 0.602$ ohm per mile.

For aluminum, this corresponds to a size between No. 00 and No. 000 B. & S. gauge. Adopt No. 000 (see Table 21).

Then, r becomes 0.5412, and

$rL = R = 0.5412 \times 40 = 21.65$ ohms.

$RI = 21.65 \times 81.5 = 1764.5.$

x (from the table) = 0.742 ohm per mile.

$xL = X = 0.742 \times 40 = 29.68$ ohms.

$XI = 29.68 \times 81.5 = 2{,}419$ ohms.

$V_G = \sqrt{(24{,}540 + 1764.5)^2 + (15{,}191 + 2419)^2} = 31{,}655$ volts.

$E_G = 31{,}655 \times \sqrt{3} = 54{,}826$ volts = voltage between wires.

$d = \dfrac{100(31{,}655 - 28{,}870)}{28{,}870} = 9.66$ per cent.

$p = \dfrac{100 \times 1764.5}{24{,}540} = 7.2$ per cent.

The power factor at the generator end will be

$$\cos \phi_G = \frac{0.85(100 + 7.2)}{100 + 9.66} = 0.835.$$

Weight of one conductor (from table) = 818 lb. per mile.

Weight of line = 3 × 815 × 40 = 98,160 lb.

Add to this 5 per cent. for the tie-wires and waste.

Total amount of aluminum necessary = 103,068 lb.

If the conditions are known at the supply or generator end only, then

$$F = V_G - P_G R - Q_G X, \tag{93}$$

and

$$S = Q_G R - P_G X. \tag{94}$$

In which V_G = voltage between any wire of the line and the neutral at the generator end.

$P = I \cos \phi \qquad Q = I \sin \phi$

X = total reactance of one wire of the line.

R = total resistance of one wire of the line.

$$V_L = \sqrt{F^2 + S^2}, \text{ or } = F + \frac{S^2}{2F} \text{ approx.}$$

For this problem, taking V_G at the value previously computed, namely 31,655 volts, and the other line constants as found,

$P = 81.5 \times 0.85 = 69.27.$

$Q = 81.5 \times 0.526 = 42.87.$

$F = 31{,}655 - 69.27 \times 21.65 - 42.87 \times 29.68 = 28{,}880.$

$S = 42.87 \times 21.65 - 69.27 \times 29.68 = -1126.$

$$V_L = 28{,}880 + \frac{1{,}267{,}876}{57{,}760} = 28{,}880 + 21 = 28{,}901 \text{ volts,}$$

which is (within 31 volts) the same as the volts to neutral at the load end assumed in the previous example. It is to be noted that S is usually negligible and, practically,

$$V_G = F = V_G - P_G R - Q_G X.$$

Long Lines.—When transmission lines exceed 40 miles in length, the effects of capacity must be considered, as they become of such importance in long lines, under very high voltage, that the inclusion of these phenomena in the computations becomes imperative. This statement also applies to short branch lines tapped from high-voltage circuits. In general, the formulæ which include the capacity, should be used when the product of the voltage, by length of transmission (in miles) by frequency in cycles per second, exceeds 15×10^7. Thus, the capacity susceptance in a line 30 miles long, tapped from a 120,000-volt, 60-cycle circuit, is greater than that of a line 80 miles long and working under a pressure of 35,000 volts at 60 cycles. The product of the three factors in the first case is 21.6×10^7 and in the second case, 16.8×10^7.

The exact solution of the voltage and current relations and

values, in a line having distributed capacity, is complex and tedious. Fortunately, however, certain approximate formulae have been developed which are comparatively easy to use and which give results so close to those obtained by the exact formulæ that the error is far less than that which would arise from the resistance of the metal varying from the standard assumed, or from the change in resistance due to the change in the temperature of the air surrounding the line. When it is considered that the resistance of copper changes approximately 0.4 per cent. per degree C. of temperature change, and that nearly every line will experience a temperature range of 35°C., with a corresponding change in resistance of about 14 per cent., the futility of attempting exact computations in the practical design of transmission lines becomes obvious.

Dwight Formulæ.—The Dwight formulæ include the capacity effects and, up to 300 miles length of transmission and 100,000 volts, give results which are within ½ per cent. of the exact formulæ.

In these formulæ, K is a constant which is numerically equal to $\frac{6f^2}{10{,}000}$, f being the frequency in cycles per second. Hence, K, for 60 cycles, is 2.16, and for 25 cycles, is 0.375.

Put $K\left(\frac{L}{1000}\right)^2 = \Delta$, L being the length of transmission, in miles.

Then, for full load,

$$A = V_L(1 - \Delta) + PR\left(1 - \frac{2\Delta}{3}\right) + QX\left(1 - \frac{\Delta}{6}\right) \tag{96}$$

$$B = \frac{V_L R\Delta}{X} + PX\left(1 - \frac{\Delta}{6}\right) - QR\left(1 - \frac{2\Delta}{3}\right) \tag{97}$$

$$C = P(1 - \Delta) + \frac{QR\Delta}{X} - \frac{2V_L R\Delta^2}{3X^2} \tag{98}$$

$$D = \frac{PR\Delta}{X} - Q(1 - \Delta) + \frac{2V_L\Delta}{X}\left(1 - \frac{\Delta}{3}\right) \tag{99}$$

$$\text{Regulation of line} = \left(\frac{V_G}{V_{OG}} - 1\right)V_L \tag{100}$$

For no load

$$A_O = V_L(1 - \Delta) \tag{101}$$

$$B_O = \frac{V_L R\Delta}{X} \tag{102}$$

$$C_O = -\frac{2V_L R\Delta^2}{3X^2} \tag{103}$$

$$D_O = \frac{2V_L\Delta}{X}\left(1 - \frac{\Delta}{3}\right). \tag{104}$$

For conditions given at the generator end, the factors, F, S, M, and N, are found by the following formulæ:

$$F = V_G(1 - \Delta) - P_GR\left(1 - \frac{2\Delta}{3}\right) - Q_GX\left(1 - \frac{\Delta}{6}\right) \qquad (105)$$

$$S = \frac{V_GR\Delta}{X} - P_GX\left(1 - \frac{\Delta}{6}\right) + Q_GR\left(1 - \frac{2\Delta}{3}\right) \qquad (106)$$

$$M = P_G(1 - \Delta) + \frac{Q_GR\Delta}{X} + \frac{2V_GR\Delta^2}{3X^2} \qquad (107)$$

$$N = \frac{P_GR\Delta}{X} - Q_G(1 - \Delta) - \frac{2V_G\Delta}{X}\left(1 - \frac{\Delta}{3}\right). \qquad (108)$$

As an example of the use of these formulæ, take the following conditions:

System, three-phase.

Load on system, 18,000 kv.a.

Power factor of load $= \cos \phi_L = 0.90$.

Kw. of load $= 18{,}000 \times 0.90 = 16{,}200$ kw.

Length of line, 300 miles.

Spacing between wires, 10 ft.

Voltage between wires at load end $= E_L = 104{,}000$ volts.

Frequency, 60 cycles per second.

Preliminary Computations for First Approximations.—

Assume the allowable energy loss in the line, at full load, to be 16 per cent.

Total kw. energy loss $= 0.16 \times 16{,}200 = 2592$ kw.

Energy loss per wire $= \frac{2592}{3} = 864$ kw.

$$V_L = \frac{E_L}{\sqrt{3}} = \frac{104{,}000}{\sqrt{3}} = 60{,}000 \text{ volts.}$$

$$I_L = \frac{18{,}000 \times 1000}{3 \times 60{,}000} = 100 \text{ amp.}$$

Approximate resistance of one wire of line

$$R = \frac{16 \times 60{,}000 \times 0.90}{100 \times 100} = 86.4 \text{ ohms (Equation 90).}$$

Resistance per mile $= \frac{86.4}{300} = 0.288$ ohm.

In a long line, the capacity effect will be so marked that a somewhat higher resistance may be adopted for the trial calculation, say 0.30 ohm, per mile.

From the table this is found to be between 0000 and 000, copper cable. Adopt 000 for the first calculations.

r = Resistance 000 copper cable for 60 cycles is 0.3391 per mile.
R = Total resistance = $0.3391 \times 300 = 101.73$ ohms.
x = Reactance per mile (from table) for 10-ft. spacing at 60 cycles = 0.797 ohm per mile.
X = Total reactance per wire = $0.0797 \times 300 = 239.1$ ohms.
$P = \cos \phi I = 0.90 \times 100 = 90.0.$
$Q = \sin \phi I = 0.436 \times 100 = 43.6.$
$\Delta = 2.16\left(\frac{L}{1000}\right)^2 = 2.16(0.3)^2 = 0.1944.$

Then

$$A = 60{,}000\,(1 - 0.1944) + 90 \times 101.7\left(1 - \frac{2 \times 0.1944}{3}\right) + 43.6 \times 239.1 \times \left(1 - \frac{0.1944}{6}\right) = 66{,}380.$$

$$B = \frac{60{,}000 \times 101.7 \times 0.1944}{239.1} + 90 \times 239.1\left(1 - \frac{0.1944}{6}\right) - (43.6 \times 101.7) \times \left(1 - \frac{2 \times 0.1944}{3}\right) = 21{,}915.$$

$$C = 90\,(1 - 0.1944) + \frac{43.6 \times 101.7 \times 0.1944}{239.1} - \frac{2 \times 60{,}000 \times 101.7}{3 \times (239.1)^2} \times (0.1944)^2 = 73.42.$$

$$D = \frac{90 \times 101.7 \times 0.1944}{239.1} - 43.6\,(1 - 0.1944) + \left(\frac{2 \times 60{,}000 \times 0.1944}{239.1}\right)\left(1 - \frac{0.1944}{3}\right) = 63.55$$

For no load

$$A_o = 60{,}000(1 - 0.1944) = 48{,}336.$$

$$B_o = \frac{60{,}000 \times 101.7 \times 0.1944}{239.1} = 4950.$$

$$C_o = -\frac{2 \times 60{,}000 \times 101.7 \times (0.1944)^2}{3 \times (239.1)^2} = -2.68.$$

$$D_o = \left(\frac{2 \times 60{,}000 \times 0.1944}{239.1}\right)\left(1 - \frac{0.1944}{3}\right) = 91.5.$$

All the conditions of operation of this line can now be determined from these quantities.

Generator voltage (to neutral) full load.

$$V_g = 66{,}380 + \frac{(21{,}915)^2}{2 \times 66.380} = 69{,}997 \text{ or, practically, } 70{,}000 \text{ volts.}$$

Voltage between wires at generator end = $E_G = 70{,}000 \times \sqrt{3} = 121{,}240$ volts.

Full-load current at generator end per wire,

$$I_G = \sqrt{(73.42)^2 + (63.55)^2} = 97 \text{ amp.}$$

Kw. output at generator end.

$$\frac{3(66{,}380 \times 73.42 + 21{,}915 \times 63.55)}{1000} = 18{,}829 \text{ kw.}$$

Total energy loss in line $= 18{,}829 - 16{,}200 = 2629$ kw.

Power factor at generator end.

$$\cos \phi_G = \frac{18{,}829 \times 1000}{3 \times 70{,}000 \times 97} = 0.925.$$

For no load and constant voltage at load end.

Generator voltage $= V_{0G} = 48{,}336 + \dfrac{(4950)^2}{2 \times 48{,}336} = 48{,}590$ volts.

That is, the voltage at the load end is greater by 21,410 volts than at the generator end, due to the effect of the capacity of the line. Measured between wires, the voltage at the generator end, or $E_{0G} = 48{,}590 \times \sqrt{3} = 84{,}160$ volts.

Charging current, is

$$I_{0G} = \sqrt{(-2.68)^2 + (91.5)^2} = 91.53 \text{ amp.}$$

Regulation of line $= \left(\dfrac{70{,}000}{48{,}590} - 1\right) 60{,}000 = 23{,}464$ volts,

which is the maximum variation of the voltage at the load end, from no load to full load, with a constant voltage at the generator end of 70,000 volts.

Kw. output at generator end, with no load at load end

$$KW_{0G} = \frac{3 \times [(48{,}336 \times -2.68) + (4950 \times 91.5)]}{1000} = 970 \text{ kw.}$$

which represents the energy lost in the line due to the flow of charging current.

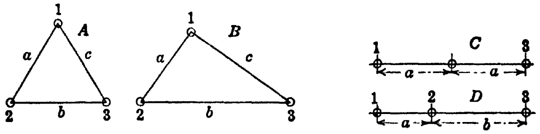


FIG. 157.—Relative positions of wires of three-phase circuit.

All the foregoing formulæ apply to balanced circuits, that is, circuits in which the current in each of the conductors has the same value. They apply to three-phase systems only when the

conductors are arranged in an equilateral, triangular relationship as indicated in A, Fig. 157.

When a three-phase circuit is disposed with its wires in triangular relationship, but not forming the apexes of an equilateral triangle, as, for instance, the arrangement shown in B, Fig. 157, the equivalent spacing, which must be adopted in fixing the values of reactance and susceptance, will be

$$S = \sqrt[3]{abc}. \tag{109}$$

In case the conductors are arranged flatwise, in a single plane, as indicated in C, Fig. 157, the numerical value of the spacing to be used for determining the reactance and susceptance is

$$S = 1.26a.^{1} \tag{110}$$

If the flat, or single-plane, arrangement is unsymmetrical, that is, the middle wire closer to one of the outside wires than to the other, as indicated in D, Fig. 157, then the spacing to be used in the formulæ is $S = \sqrt[3]{abc}$. These values are based on transposition of the wires so that the "exposures" are substantially equal, as explained in the section on "Transposition of Conductors."

Convergent Series Formulæ.—The simplest exact formulæ for a transmission line are those which are deduced by the use of an infinite or convergent series. An infinite series consists of an infinite number of terms and is called convergent if their sum has a definite, finite value. The characteristic property of a convergent series is that by taking a sufficiently large number of terms, a sum is obtained which differs from the sum of the entire series by a negligible amount. The more rapidly the series converges, the fewer are the terms needed for the practical purpose of getting a sufficiently accurate sum. It is always possible to take a sufficient number of terms to make the approximation fall within the required limits.

To make any practical use of the accurate formulæ, complex quantities must be employed. A discussion of this branch of mathematics is beyond the scope of this work. It is, however, not necessary to have a full knowledge of the complex quantities in order to make all the computations required for transmission lines.

Complex quantities are made up of two kinds of quantities called the "real" and the "imaginary" parts. The real part is

[1] See "Transmission Line Formulæ," by HERBERT BRISTOL DWIGHT.

simply a numerical or algebraic quantity. The imaginary part is, likewise, an ordinary quantity but has the designating letter j before it to distinguish it. If, in multiplication, the j disappears, the quantity then becomes a real part.

In adding complex quantities, the real parts are added, and the imaginary parts are added, separately, the sum being a complex quantity, with a real and an imaginary part. Real and imaginary parts cannot be added algebraically. They can be added vectorially only. Physically, the real part of a complex quantity used in electrical calculations, gives the values of those factors of current and electromotive force in phase with each other, while the imaginary part gives the values of the components that are out of phase. A complex quantity may also be represented graphically by a point referred to the axes X and Y at right angles to each other, the abscissa being A and the ordinate B. This representation leads to the so-called vector analysis, the vector of a quantity $A + jB$, being the length of a line from the orgin of the axes to the point (A, B). Clearly, the vector of $A + jB$ is, therefore, $\sqrt{A^2 + B^2}$, this being its numerical value.

As an example of the method of addition, take the complex quantities

$$\begin{array}{r} 8 + j10 \\ 34 - j18 \\ -\ 7 + j23 \\ \hline 35 + j15 \end{array}$$

The sum is $35 + j15$

The following rules of multiplication cover all the information essential

$$+j \times +j = -1$$
$$-j \times +j = +1$$
$$-j \times -j = -1$$

That is, when two j quantities are multiplied together, the j cancels out, and if the signs of the two quantities are alike, the sign of the product is minus, while if the signs of the two quantities are unlike, the sign of the product is plus.

With a clear understanding of the addition and multiplication of complex quantities, they may be used for making transmission-line calculations, without further knowledge of the subject.

For a transmission line, with the conditions given at the

load end. To find the quantities A and B, as used in the equations previously given in this chapter, the formula is

$$A + jB = V_L\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{24} + \frac{Y^3Z^3}{720} \dots \text{etc.}\right) + (P - jQ)Z\left(1 + \frac{YZ}{6} + \frac{Y^2Z^2}{120} + \frac{Y^3Z^3}{5040} + \dots \text{etc.}\right) \quad (111)$$

In which, $Z = R + jX$.

$Y = bL$ = capacity susceptance per mile for one wire, multiplied by the length of transmission (see Table 25).

R = total resistance of one wire.
X = total reactance of one wire.
$V = 0.577E$.
E = voltage between wire.

When the equation is solved, the sum of all the real quantities on the right-hand side $= A$, while the sum of all the j quantities $= B$.

The formula for the quantities C and D is

$$C + jD = (P - jQ)\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{24} + \frac{Y^3Z^3}{720} \text{ etc.}\right) + V_LY\left(1 + \frac{YZ}{6} + \frac{Y^2Z^2}{120} + \frac{Y^3Z^3}{5040} + \dots \text{etc.}\right) \quad (112)$$

For no load, the formula for the quantities A_0 and B_0 is

$$A_0 + jB_0 = V_L\left[1 + \frac{YZ}{2} + \frac{Y^2Z^2}{24} + \dots\dots\right]. \quad (113)$$

The formula for the quantities C_0 and D_0 is

$$C_0 + jD_0 = V_LY\left[1 + \frac{YZ}{6} + \frac{Y^2Z^2}{120} + \dots\dots\right]. \quad (114)$$

Except in the case of very long lines, all the terms that are squares and higher powers of Y and Z may be suppressed, the first power terms only, being used. The inaccuracy resulting from this suppression of the higher-power terms is negligible if the line be less than 300 miles in length. In no case is it necessary to use any term that is a higher power of Y or Z than the square.

Taking the foregoing formulæ with the higher powers of Y and Z suppressed, they become

For full load

$$A + jB = V_L\left(1 + \frac{YZ}{2}\right) + (P - jQ)Z\left(1 + \frac{YZ}{6}\right) \quad (115)$$

$$C + jD = (P - jQ)\left(1 + \frac{YZ}{2}\right) + V_LY\left(1 + \frac{YZ}{6}\right) \quad (116)$$

For no load

$$A_0 + jB_0 = V_L\left(1 + \frac{YZ}{2}\right) \tag{117}$$

$$C_0 + jD_0 = V_L Y\left(1 + \frac{YZ}{6}\right) \tag{118}$$

The methods of using these formulæ are best indicated by applying them to the solution of a definite problem. In order to compare the results with the approximate formulæ, the same example that has been used to show the application of Dwight's formula, will be taken.

The line constants are here repeated for convenience.

L = distance of transmission, 300 miles; system, three-phase, 60 cycles. Load on system, 18,000 kv.a.
ϕ_L = power factor of load, = 0.90.
Kw_L = Kw. of load = 18,000 × 0.90 = 16,200 kw.
S = spacing between wires, 10 ft.
E_L = voltage between wires at load end = 104,000 volts.
V_L = voltage between any wire and neutral at load end = $\frac{104{,}000}{\sqrt{3}}$ = 60,000 volts.
R = total resistance of one wire = 101.7 ohms.
X = total reactance of one wire = 239.1 ohms.
Y = total capacity susceptance of one wire = 5.39×10^{-6} per mile = 0.001617 mhos, total.
I_L = current in one wire at load end, at full load = 100 amp.
P = $I_L \cos\phi$ = 90 amp.
Q = $I_L \sin\phi$ = 43.6 amp.

Remembering that in practice, the formula is seldom carried beyond the value of Y^2Z^2, the values become:

$$Y = jb = j0.001617$$
$$Z = R + jX = 101.7 + j239.1$$
$$YZ = j0.001617\,[101.7 + j239.1] = j0.1644 - 0.38662$$
$$\frac{YZ}{2} = j0.0822 - 0.19331 \qquad \frac{YZ}{6} = j0.0274 - 0.06443$$

$$Y^2Z^2 = \left\{\begin{array}{l} j0.1644 - 0.38662 \\ \underline{j0.1644 - 0.38622} \\ -0.027027 - j0.06356 \\ \underline{+0.149475 - j0.06356} \end{array}\right.$$
$$Y^2Z^2 = \quad +0.122348 - j0.12712$$

$$\frac{Y^2Z^2}{24} = +0.005098 - j0.005297$$

$$\frac{Y^2Z^2}{120} = +0.001019 - j0.001059$$

$$(P - jQ)Z = (90 - j43.6)\ (101.7 + j239.1)$$

$$\begin{array}{r} +101.7 + j239.1 \\ +90 - j43.6 \\ \hline +9{,}153 + j21.519 \\ +10{,}425 - j4434 \\ \hline \end{array}$$

$$(P - jQ)Z = +19{,}578 + j17{,}085$$

$A + jB = 60{,}000\,[1 + j0.0822 - 0.19331 + 0.005098 - j0.005297] + (19{,}578 + j17{,}085)(1 + j0.0274 - 0.06443 + 0.001019 - j0.001059)$.

Collecting the real and imaginary quantities

$$\begin{aligned} A + jB &= 60{,}000\,(0.811788 + j0.076903) \\ &\quad + (19{,}578 + j17{,}085)(0.936589 + j0.026341) \\ &= 48{,}707 + j4614 + 18{,}338 + j516 + j16{,}002 - 450 \\ &= 66{,}595 + j21{,}132 \\ \text{or } A &= 66{,}595 \\ B &= 21{,}132 \end{aligned}$$

Also

$$\begin{aligned} C + jD &= (90 - j43.6)\ (0.811788 + j0.076903) \\ &\quad + 60{,}000 \times j0.001617(0.936589 + j0.026341). \end{aligned}$$

(The quantities in the right-hand parentheses are the same as those in the corresponding parentheses found when calculating the value of $A + jB$.)

$$\begin{aligned} C + jD &= 76.41 - j28.47 + j90.87 - 2.55 \\ &= 73.86 + j62.40 \\ C &= 73.86 \\ D &= 62.40 \end{aligned}$$

For no load

$$\begin{aligned} A_o + jB_o &= 60{,}000\,[1 + j0.0822 - 0.1933 + 0.005098 - j0.005297] \\ A_0 &= 48{,}707 \\ B_0 &= 4{,}614 \\ C_o + jD_0 &= 60{,}000 \times j0.001617[1 + j0.0274 - 0.06443 + 0.001019 - j0.001059] \\ C_0 &= -2.55 \\ D_0 &= 90.87 \end{aligned}$$

$$V_G = 66{,}595 + \frac{(21{,}132)^2}{2 \times 66{,}595} = 69{,}948 \text{ volts to neutral.}$$

$$E_G = 69{,}948 \times \sqrt{3} = 121{,}150 \text{ volts between wires.}$$

$$I_G = \sqrt{(73.86)^2 + (62.40)^2} = 96.7 \text{ amp. per wire.}$$

$$V_{0G} = 48{,}707 + \frac{(4164)^2}{2 \times 48{,}707} = 48{,}936 \text{ volts to neutral.}$$

$$E_{0G} = 48{,}936 \times \sqrt{3} = 84{,}757 \text{ volts between wires.}$$

$$I_{0G} = \sqrt{(-2.55)^2 + (90.87)^2} = 90.88 \text{ amp. per wire.}$$

By inspection of the quantities, it is obvious that the results obtained by Dwight's formulæ are, practically, the same as computed by the convergent series, although the example chosen is for a very long line, namely, 300 miles.

It is also seen that the suppression of all the terms of Y and Z, higher than the first power, will give, substantially, the same results, the effect of the higher powers of these quantities being very small, and, for all practical purposes, negligible.

The foregoing examples show that with a long line and high voltage the generator current at zero load may be nearly as great as the current at full load, and is appreciable for even shorter lines. This, however, is simply line-charging current and does not represent any considerable energy output, because the current is not in phase with the electromotive force. The actual energy delivered by the generator when there is no energy supplied at the load end, is comparatively small, as has been shown in the previous computation. The 300-mile line that delivers 16,200 kw. to the full load has an energy loss in the line of 989 kw. at no load, or little over one-third the line loss when supplying full load.

Although the large capacity current does not give any considerable energy output, it is just as effective as energy current in heating the generators, transformers, and transmission line, so that all the generating apparatus will be kept at, practically, as high a temperature at zero load as at full load. Also, in order to prevent injurious temperatures in the windings, as many generators will have to be kept working as if the system were fully loaded

A curious effect caused by the capacity current, in long lines, is that of a large current at the generator end when there is zero load at the load end, and then as load is gradually imposed on the system, the generator current diminishes until a minimum

point is reached, after which the current will begin to increase with augmentation of the load.

It is to be noted that none of the formulæ, herein given, provides for the determination of R or the size of the wire. A formula from which the exact value of R can be computed is, of course, possible to derive. It is, however, so long and cumbersome that it has no practical value. An approximation of the size of the wire can be quickly made in the manner previously set forth and, by any of the formulæ given, the exact loss and regulation can be determined. If the values found are too great or too small, another size of wire may be chosen and the process repeated. In other words, a trial and error method is shorter and less liable to arithmetical errors than the direct solution would be.

Tables.—The tables at the end of this chapter, give the values of inductance and capacity per mile, of a single wire, at frequencies of 60 cycles, and they are sufficiently complete to cover nearly every practical case.

For frequencies other than 60 cycles, take from the table the value corresponding to the size of the wire and distance of separation, multiply by the required frequency, and divide the product by 60. Thus, the inductive reactance in the table for a 0000 wire, with 6-ft. spacing, is 0.728 ohms per mile. For 100 cycles, per second, the value should be $\frac{0.728 \times 100}{60} = 1.213$ ohms per mile. The reactance for any set of conditions may be computed from the formulæ given above each of the tables.

Resistance of Cables.—Since cables are made up of twisted wires, the length of any strand is greater than the distance over which the cable extends. Also, the coating of metallic oxide on the surface of each strand tends to make the current follow the helical, or twisted, paths of the individual strands, which is the equivalent of a slight increase in the resistance of the cable as compared with the resistance of an equivalent solid conductor.

Skin Effect.—The electromagnetic variations inside a conductor carrying alternating current, tend to crowd the current toward the outside portions of the wire, and, therefore, the current density is less at the center of the wire than near its periphery. This phenomenon is called "skin effect." Its

effect is to make the ohmic resistance of a conductor greater for alternating than for direct currents.

With small wires and low frequencies, this effect is negligible, but with large sizes of cables—above 0000, and frequencies of 60 cycles per second—the increased resistance and its effect on the regulation of transmission lines, becomes appreciable.

In the tables of resistances given in this chapter, the figures under the different frequency headings, give the values of the resistances, which include the added resistance due to the skin effect, and no computation is necessary to compensate for it.

Temperature Coefficient.—As indicated in the table of characteristics of copper and aluminum, the former has a temperature coefficient equal to nearly 0.004 or 0.4 of 1 per cent., while the aluminum has a coefficient of about 0.0022, per degree C. This means that with change in temperature, the resistance of a wire undergoes a proportional change. Hence, in specifying the resistance of any conductor, the temperature must, also, be fixed.

The standard value, as given in the table, and adopted by the engineering profession, is 20°C. or 68°F.

Taking aluminum as an example, and selecting No. 0000 cable, its resistance is found to be 0.4288 ohm per mile at 20°C. and its temperature coefficient is 0.0022.

At 35°C. the resistance will be $0.4288\ [1 + (35 - 20)\ (0.0022)] = 0.4429$ ohm.

The formula for change in resistance for temperature above or below 20°C. is

$r_2 = r_1(1 + (t - 20)k)$ (119).

r_1 = tabular value of the resistance at 20°C.

t = temperature in degrees C. at which resistance is to be found.

k = temperature coefficient.

Of course, if t is less than 20, and the quantity $t - 20$ is negative, r_2 becomes less than r_1.

Separation of Wires.—The distance apart of wires varies with the voltage, the span, the kind of wires, and the form of support.

Clearance between lines in two vertical planes is fixed by considerations given later under discussion on "Sag."

TABLE 16.—MINIMUM SEPARATION OF CONDUCTORS

Length of Span	150 ft.	250 ft.	350 ft.	500 ft.	650 ft.	800 ft.	Clearance wire to support
Kilo-volts	Distances apart of wires, in inches						
Pin insulators:							
Not exceeding 6.6	24	30	36	48	60	72	12
Over 6.6 to 22.0	32	37	42	54	65	76	14
Over 22.0 to 44.0	46	50	56	64	74	82	16
Over 44.0 to 66.0	58	62	66	72	82	88	22
Over 66.0 to 88.0	72	74	78	84	90	96	27
Suspension insulators:							
Not exceeding 44.0	48	56	62	72	86	100	16
Over 44.0 to 66.0	66	72	77	86	98	112	22
Over 66.0 to 88.0	80	86	91	102	112	125	27
Over 88.0 to 110.0	93	98	104	115	124	135	48
Over 110.0 to 140.0	110	114	120	127	136	148	54
•Over 140.0 to 165.0	120	126	132	138	147	157	60

Compensation for Line Drop.—From the discussion of "Electric Circuits," it may be seen that a condenser at the load end of a long line would help to reduce the voltage drop at times of heavy load, and an inductance would keep the voltage within normal limits at the load end when the load is small, without the necessity of lowering the voltage at the generator end.

A synchronous motor, running without external load, will act as a condenser of high capacity if the excitation of the field magnets be greater than that normally required, and when thus "over-excited," will deliver a leading current to the line.

Also, when the machine is under-excited, it will act as an inductance and take lagging current from the line. From which, it follows that an unloaded synchronous motor, at the load end of the line, will allow the use of a smaller line conductor and keep the regulation better than it would be without this machine.

For a full discussion of this subject, the reader is referred to the writings of Dwight,[1] Hagood,[2] Andrus[3] and others.

The synchronous motor compensates for the so-called "wattless" component of the current. The capacity of the synchro-

[1] "Constant-voltage Transmission."
[2] *Trans.* A. I. E. E., December, 1913.
[3] *Trans.* A. I. E. E., March, 1913.

nous motor may be any amount that seems commercially judicious up to the maximum value of the kv.a. given by the volts at the receiver end multiplied by the value of the out-of-phase current. The greater the size of the motor, the more completely are the reactive and condensance currents neutralized. The question is one that depends largely on the length of line, frequency and the regulation required. The total cost of motors and line metal is usually less for the same degree of regulation obtained when the lines exceed 60 miles in length.

Corona.—When the voltage of a circuit exceeds a value that is fixed for the specific constants of the line and surrounding air, a critical point is reached, at which, the electrostatic stresses in the air surrounding the wires are nearly at the point of rupture of the air. The wires are then surrounded by a dim, violet-colored light, which appears like an enveloping tube of bright mist. This light is visible in the dark and is called the "corona." When this stage is reached, there is an actual electrical discharge from one wire to the others, and this discharge represents an energy loss.

The study of this phenomenon possesses considerable interest, but its practical aspects only, can be included in this discussion. Since the development of the suspension insulator, the limit of voltage for transmission is fixed by the corona effect, and it must be duly considered in the design of transmission lines. Many investigators have made experiments to determine the limiting values of the line voltage for a given set of conditions, and the line losses which follow the application of a disruptive voltage. The experiments of Ryan and of Mershon were the pioneer investigations, and while their general conclusions were in substantial agreement, their constants differed considerably. Later experiments have brought the constants into accord, and the present formula of Peek is regarded as accurate and reliable.

This formula is

$$V = 123 \times 10^3 rm\delta \log_{10} \frac{S}{r} \tag{120}$$

For 3-phase cicrūits, $V = \frac{E}{\sqrt{3}}$ = voltage at which disruption is impending of any wire to neutral; that is, the limiting line voltage to neutral.

E = volts between wires.
m = factor of roughness.
δ = air density factor.
r = radius of conductor, in inches.
S = separation of conductors in inches.
m = 1, for polished wires.
= 0.93 to 0.98 for rough or weathered wires.
= 0.83 to 0.87 for cables.

δ varies with the altitude and temperature and is

$$\delta = \frac{17.9b}{459 + t} \tag{121}$$

b = height of barometer, in inches.
t = temperature of surrounding atmosphere, in degrees F.

This formula is for three-phase circuits, arranged in equilateral triangular relation. When the three wires are in one plane, the air surrounding the middle wire will be subjected to a greater electrostatic stress than will either of the other two. Corona will form on the middle wire at about 4 per cent. lower voltage than that given by the formula.

This formula is equally applicable to single-phase, or two-phase circuits, in which case, $V = \frac{E}{2}$.

The following table shows the voltages at which corona will form, at sea level, for smooth wires and for cables.

TABLE 17.—CORONA LIMITS OF VOLTAGE. KILOVOLTS BETWEEN LINES (THREE-PHASE) AT SEA LEVEL
(CABLES)

From formula $e_o = \sqrt{3}\, g_o m_o r \delta \log_e \frac{S}{r}$, where $m_o = 0.87$

g_o = disruptive gradient for air = 29.8 KV. per cm. max., or 21.1 KV. per cm. for $e = \sqrt{\text{mean}^2}$.

A.W.G.	Diam., in.	Spacing—ft.									
		3	4	5	6	8	10	12	14	16	20
4	0.230	.....	56	58	60	62	64	66	68	69	71
3	0.261	....	62	65	67	70	72	74	76	77	80
2	0.290	.....	.....	71	73	76	79	81	83	85	87
1	0.330	....	.....	79	81	85	88	91	93	95	97
0	0.374	...	....	.....	90	95	98	102	104	106	109
00	0.420	.....	.....	....	98	104	108	111	114	117	121
000	0.470	....	.....	.....	.....	114	118	121	124	127	132
0000	0.530	.....	.....	.....	.....	125	130	135	138	141	146

TABLE. 17.—CORONA LIMITS OF VOLTAGE. KILWOLTS BETWEEN LINES (THREE-PHASE) AT SEA LEVEL (*Continued*)

(CABLES)

From formula $e_v = \sqrt{3}\, g_o m_o r\delta \log_e \frac{S}{r}$, where $m_o = 0.87$

A.W.G	Diam., in.	Spacing—ft.									
		3	4	5	6	8	10	12	14	16	20
250,000	0.590	.....	.....	.....	.....	138	144	149	152	156	161
300,000	0.620	.....	.....	.....	.....	.....	151	156	161	165	171
350,000	0.679	.....	.....	.....	.....	.....	161	166	170	175	180
400,000	0.728	.....	.....	.....	.....	.....	171	176	180	185	192
450,000	0.770	.....	.....	.....	.....	.....	178	184	190	194	200
500,000	0.818	.....	.....	.....	.....	.....	188	194	199	205	210
800,000	1.034	.....	.....	.....	.....	.....	.....	234	241	244	256
1,000,000	1.152	.....	.....	.....	.....	.....	.....	256	264	270	281

(SOLID WIRES) $m_o = 0.93$

A.W.G.	Diam. in.	Spacing—ft.									
		3	4	5	6	8	10	12	14	16	20
4	0.204	51	54	56	58	60	62	64	65	66	68
3	0.229	..	59	62	64	66	68	70	72	74	76
2	0.258	..	..	69	70	74	76	78	80	82	84
1	0.289	..	..	75	77	81	83	86	88	90	92
0	0.325	..	..	..	85	89	92	95	97	99	102
00	0.365	..	..	..	94	98	102	105	107	110	113
000	0.410	..	..	..	..	109	113	116	119	121	124
0000	0.460	..	..	..	..	120	125	128	131	134	138

The following table shows the change in the value of the factor δ for various altitudes at a temperature of 60° F. This table is computed from formula (121).

TABLE 18.—ALTITUDE CORRECTION FACTOR δ

Altitude, ft.	δ	Altitude, ft.	δ	Altitude, ft.	δ	Altitude, ft.	δ
0	1.00	2,000	0.92	5,000	0.82	9,000	0.71
500	0.98	2,500	0 91	6,000	0.79	10,000	0.68
1,000	0.96	3,000	0.89	7,000	0.77	12,000	0 63
1,500	0.94	4,000	0.86	8,000	0.74	14,000	0.58

As is obvious from the formula, the limiting voltage varies with $r \log \frac{S}{r}$. This portion of the formula can be increased in value only by increasing r and S. This means that the radius of the wire should be as great as possible, and, to offset the reduction in the fraction $\frac{S}{r}$ caused by the increase in r, S must be increased. Since, however, $\frac{S}{r}$ appears in the formula in a logarithmic form, the increase in separation of the wires becomes less and less effective, until, finally, any increase in separatio will give no further appreciable increase in the line voltage. Up to a separation of 75 to 80 times the radius of the wire, small changes in the amount of separation give almost proportional changes in the allowable line voltage. When this limit of $\frac{S}{r}$ is reached, the change in allowable line voltage varies but slowly with the change in its value. Thus, if a wire be 0.5 in. in diameter (about No. 0000) and the separation be 25 in.,

$$\frac{S}{r} = 100, \text{ and } \log \frac{S}{r} = 2.$$

If the separation be made ten times as great as at first, or 250 in.,

$$\frac{S}{r} = 1000 \text{ and } \log \frac{S}{r} = 3.$$

In other words, if the separation be made ten times as great, after $\frac{S}{r}$ passes a value of 100, the allowable voltage is increased only 50 per cent. above that given by the smaller value of $\frac{S}{r}$.

The maximum possible electrostatic separation between any two wires is the sum of the heights of the wires above the ground. Any greater electrostatic separation is not possible because the earth forms a conductor and the electrostatic stress would exist from the two wires to the ground, if their distance apart were greater than the sum of their heights above ground.

This is the reason why wooden crossarms on poles make a better support for a transmission line than steel crossarms and towers. In case of wooden crossarms on poles, the actual, measured distance apart of the wires is the electrostatic separation and is the value to be used in formula 120.

In the case of conductors supported on metallic structures, the value of S is not necessarily the distance between the wires,

but the actual distance that the current would have to pass through air in travelling from one wire to the other, using also as a path any conducting structure that might lie within the shortest air path between the two. For instance, a line supported by suspension insulators hung from metallic crossarms will have a distance of electrostatic separation between wires equal to twice the distance from the wire to the metallic support of the topmost insulator section, if this length happens to be less than the actual distance between wires.

This assumes, of course, that "flashover" will take place across the entire insulator string, rather than from disk to disk. If there is a conductor lying between the two wires, such as a steel tower, then the electrostatic distance of separation of the wires is equal to the sum of the distances from the two wires to the tower.

It frequently is necessary to compute the limiting voltage between conductors and adjacent metallic objects. The value of r to be used in such cases is that of the smallest radius for either charged body, whether it be that of the curvature of the wire or that of the portion of the metallic object closest to the wire. Also, the fact that the radii of curvature may be in different planes makes no difference in the allowable voltage. For instance, if two wires were at right angles to each other, the corona and discharge would take place just as readily as if they were parallel, except that in the former case, the phenomena would be manifested only in the short lengths of the wires which lay in the crossing point, while in the latter, the effect would cover the entire length of the wires.

The formation of corona and the discharge are always dependent on the electrostatic stresses near the surfaces of the wires, and, for a given voltage, these stresses are inverse functions of the radius. From the formula and the discussion it is obvious that for very high voltages, large diameter wires are required. The object of high voltage is, however, to diminish the amount of metal required for the conductors. Hence, for a high voltage, large wires having a small cross-section of metal are required, and this means a tubular conductor.

It has been suggested that hemp-cored cables would be suitable for these conditions. They have been tried with copper as the conducting metal, but these cables have proven unsatisfactory due to mechanical failure which was caused by the actual

eating away of the copper strands. Although most engineers have abandoned this idea because of the troubles which developed, it is probable that the corrosion of the metal may be prevented and a successful cable be made with a hemp core. Some aluminum cables with steel core have been used. These give a much larger radius for the same cost than do solid cables of either aluminum or copper, and, moreover, they have greater strength. The characteristics of these bimetallic wires are set forth in Chap. VI.

Surge Voltage.—If the self induction L, in henrys, of one wire of a line be known, and the capacity C, in farads, of one wire to neutral be known, either for the whole length of transmission, or for any unit length, the quantity, $\sqrt{\frac{L}{C}}$ is called the *natural impedance of the line.*

Combining constants,

$$\sqrt{\frac{L}{C}} = 138 \log \frac{D}{r}$$

In which

D = distance of separation of wires, in inches.
r = radius of wire, in inches.

The maximum voltage which can be set up by surges is equal to the maximum value of the current multiplied by the natural impedance.

The maximum value of the current wave is $1.41I$, where I is the effective amperes per line.

Hence the maximum possible surge voltage is

$$V_{s\,max} = 194.6 I \log \frac{D}{r}$$

In average practice, $V_{s\,max}$ = 200 to 250 times I.

TABLE 19.—SPARKING DISTANCES

In. clearance	Arcing voltage
3.375	66,000
4.0	83,000
5.0	104,000
6.0	108,000
7.0	109,000
8.0	116,000
9.0	125,000
10.0	136,000
11.0	146,000
12.0	153,000

Sparking Distances.—The actual distance across which an arc will spring, under varying conditions of voltage (maximum of wave), form of electrodes, and weather, has been experimentally determined by many investigators. The preceding table is useful, because the experiments were made on transmission wires, No. 000 B. & S. gauge cables, supported on standard insulators, on a 65-ft. steel tower.[1]

Transposition of Lines.—Where two wires are parallel and carry alternating currents, the alternating magnetic flux set up by each wire will interlink with the adjacent wire and produce in it an alternating electromotive force. This induced electromotive force adds itself, vectorially, to the impressed and other electromotive forces of the system, thereby producing a change in voltage in the particular wire subjected to the influence of the one adjacent and parallel to it.

When the wires that interact on each other are conductors of the same circuit, the electromagnetically produced voltages are simply the self-induction of the line, and make up the reactance, denoted by X, in the transmission-line formulæ. If a three-phase circuit has its wires so arranged that they form the apexes of an equilateral triangle, as in A, Fig. 157, the interaction of the alternating magnetic flux is equally divided, and the voltage induced by it is the same for each wire. Hence, there is no voltage difference between any individual wire of the circuit and the other two, due to the induced electromotive forces, because each conductor is equally affected.

If, however, the wires of a three-phase circuit are not equidistant from each other, an unbalancing of the electromotive force between phases will result, because the wire furthest from the other two will be less affected by the alternating magnetic flux than the other two.

If the three wires of a three-phase circuit are placed on the same crossarm, or in the same plane, either horizontal or vertical, the middle wire will, obviously, be more affected than will either of the outside ones.

In order to compensate for these inequalities of mutually induced electromotive force, it is necessary to transpose the relative locations of the wires, so that each wire, taken over its whole length, is affected to the same degree as each of the other two. No transposition of wires is necessary in the case of an

[1] Locke Insulator Laboratory.

equilaterally disposed three-phase circuit, for any purpose of balancing the circuit itself. It is, however, customary to transpose such circuits in order to avoid inductive effects on other circuits which may be run on the same poles, or on any nearby lines. This applies, more particularly, to telephone circuits that are near transmission lines, and over which conversation is practically impossible, unless the wires of one or both circuits are transposed.

Where two three-phase circuits are run on the same supports or near each other, one or both of the circuits must be transposed, in order to prevent unbalancing.

The transposing of circuits is a simple, mechanical operation and may be done in a number of ways. The object to be attained is to make each wire occupy successive positions with respect to the other two, such that the total magnetic flux interlinked with the wire, taken over its whole length, is the

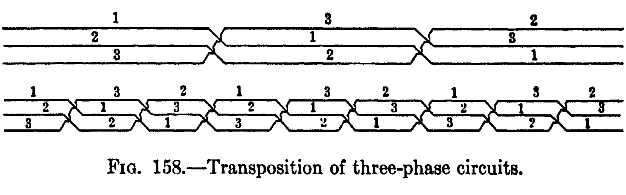


FIG. 158.—Transposition of three-phase circuits.

same as the total flux interlinked with any other wire of the circuit.

In the case of the three wires of a three-phase circuit, unsymmetrically spaced, or arranged in one plane, the transposition would be as shown in the upper circuit in Fig. 158. It is seen that wire No. 1 occupies, successively, a position on the upper side of the group for one-third the distance of transmission, a position on the lower side for one-third the distance, and a position in the middle for the same distance. Also, each of the other wires occupies two outside and one middle position, each for one-third the length of the line.

Obviously, if there were six positions of the three wires, the length of wire in each position being one-sixth of the total length of the line, the same result would be accomplished. The number of transpositions must be a multiple of the number of wires of a circuit and the distances between transposition points must be equal.

If Fig. 159 represent successive pole heads at transposition points, the numbering of the insulators shows the manner in which the wires are shifted in position. It is customary to give them a right-hand twist, or turn, of one-third of a complete rotation at each transposition point. Specially arranged pole or tower heads are necessary at transposition points, as described in Chap. VIII.

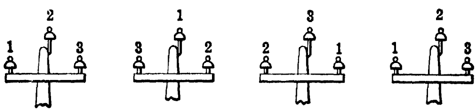


FIG. 159.—Transposition of three-phase circuits.

If two circuits be placed on the same poles, as indicated in Fig. 160, one of the circuits must have its wires transposed in order to avoid unbalancing.

From the figure, it is clear that wires *c* of circuit No. 1, and *d* of circuit No. 2, are more affected by the magnetic flux of the

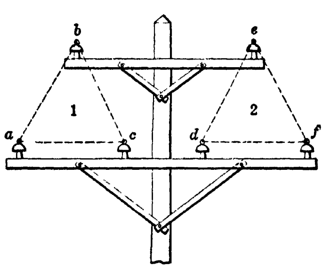


FIG. 160.—Two three-phase circuits on single pole.

adjacent circuits than are any of the other lines; also, that wires *a* and *f* are least affected. If one of the circuits be transposed, however, any unbalancing due to the mutual induction of the two circuits is eliminated. If both circuits are transposed, one circuit must make three transpositions to each transposition of the other as indicated in Fig. 158.

CHAPTER XI

DEFLECTION AND MECHANICAL STRESSES IN TRANSMISSION LINES

In the stringing of wires, or cables, on insulators, it is essential that they be pulled up with a tension that will give a certain and definite deflection, or "sag." Obviously, the sag will vary with changes in temperature, and, also, with any change in the loading, due to the addition of sleet, snow, ice, and wind loads.

The sag should be as small as possible. In determining the allowable sag, it is necessary to consider the limits of the strength of the conductor, the loading it will be subjected to, and its minimum length at the lowest temperature assumed for the territory through which it passes. If the sag be great, the poles, or towers, which form supports for the line must be correspondingly high, in order that the required clearance between the ground and the lowest point in the line may be preserved. This means that the cost of the supporting structures must be increased with increase in the maximum sag. Also, the greater the sag, the greater must be the distance of separation between the wires, which, in turn, requires that the crossarms be longer for a large sag than for a small deflection.

If the sag be too great, it will be difficult to provide a single supporting structure which will carry several wires without danger of an occasional contact between adjacent conductors. If, however, the sag be too small, the stresses in the wires may become so great that they will break, or, if the cables be strong enough to endanger the supports, added strength must be given them to prevent rupture when the wires are ice-loaded and at low temperature.

Hence, it is clear that the determination of the allowable sag when the wires are erected, is most important.

Also, the sag has a definite bearing on the spacing to be adopted for the supports. The height of all transmission-line structures is fixed by the necessity of keeping the lowest point of the wires a predetermined distance above the ground. This is not for any scientific reason, but simply to protect the line from injury

by short-circuiting caused by small wires, strings, sticks or other articles thrown over the wires, or accidental contacts from other causes.

As will be shown, the sag increases with the square of the span for a given limiting stress in the wire. Hence, if H is the height that the lowest point of the wire must be above the ground, the height of the support must be $= H + \phi L^2$, L being the length of span, and ϕ a coefficient which depends on the allowable stress in the wires.

From this relation, it is clear that the height of the supports must increase greatly with increase in the span. The cost of supporting structures increases much more rapidly than the first power of the increase in height, the cost being nearly as the cube of the height. Hence, the cost of the supporting structures increases very rapidly with increase in the span.

After the character of the supporting structure and the span have been decided on, the following conditions of deflection, sag, side swing, tension in conductors and lengths of wire between spans must be determined.

1. The deflection in the wire for a vertical loading of its own weight plus that of an ice coating (if any), together with a horizontal wind load.

This is, usually, the most severe condition that the mechanical strength of the line will have to meet, and a line designed to withstand the stresses imposed by it will be amply strong for any other set of conditions that can possibly arise. If there is no ice load to be allowed for, then the condition of maximum stress occurs at the lowest temperature the wire will ever attain.

2. Having found the deflection of the wires under the condition of maximum stress, the length of wire between supports must be computed. This length is greater than the unstressed length of the wire, due to the fact that there is an elongation produced by the stress in the wire. While it may appear that this is a mere academic factor and of no practical importance, it must be remembered that extremely small changes in the length of a wire will make appreciable changes in the deflection, and with the long spans that are in general use at the present time, the elongation due to the loading and within the elastic limit of the metal of which the conductor is made is considerable, amounting to as much as a foot in a 600-ft., span under severe conditions of loading.

3. After finding the length of wire (unstressed length) required for the most severe conditions of loading, the deflections for minimum and maximum temperatures must then be found. The calculation for minimum temperature may be omitted, if the condition for maximum loading be taken within 30°F. of the minimum temperature. The sag at the maximum temperature fixes the height of the supporting structures.

4. The "swing," or side deflection is of no importance and need not be computed, except for the rare condition of the transmission wires passing near to a house, bridge or some other structure. In such cases, it is good practice to place the supports closer together than the standard line spacing adopted and, thereby, limit the "swing" and sag.

The swing of suspension insulators is, however, important as it fixes the length of the crossarms required to give proper clearance between the wire and the pole, or tower.

The assumption of the worst conditions to which a line will be subjected over a long term of years is dependent, of course, on the part of the world in which it is located and, therefore, must be settled for each particular case by the designer. In the United States, the following is considered good, average practice.

From the 42d parallel of latitude, north to the Canadian boundary, take a loading of ice ¾ in. in thickness, the temperature of the line being 10°F., and, coincident with this maximum vertical loading, add a horizontal load, based on a wind pressure of 10 lb. per square foot. The minimum line temperature is taken as 25°F. below zero, or − 25°. Of course, the air temperature will fall below this assumed minimum, but the line temperature is higher than that of the surrounding air, due to the current flow, and consequent heat loss in the line. No wind pressure is assumed at the time of lowest temperature. The maximum temperature is taken at 110°F. This is for the wires exposed to the sun, and with current flow through them.

For the section in the latitude between the 38th and 42d parallels, the ice loading may be taken at ½ in. thick and coincident temperature 20°F., with a wind load of 10 lb. per square foot. Minimum temperature of line, zero. Maximum temperature, 120°F.

For the section lying between the 34th and 38th parallels, take the ice load at ¼ in. thick and coincident temperature at

20°F., with a wind load of 10 lb. per square foot. Minimum temperature of wires 10° and maximum temperature 120°F.

For those sections below the 34th parallel, the condition of maximum stress will be at the lowest line temperature, which should be taken at 15°F., with a coincident wind load of 10 lb. per square foot. No ice load. Maximum temperature, 140°F.

Of course, these general conditions are subject to many modifications to conform to the climate of the particular locality in which the line may be constructed. For instance, the Pacific Coast climate is less rigorous and subject to smaller differences of temperature change than the climate on the Atlantic Coast, lying in the same latitude. Also, there are great differences between the conditions to which a line will be subject if built along a mountain range or in the lowlands.

The climatic conditions also influence the maximum allowable voltage of the line due to the corona effect, and, also, the amount and character of the lightning protection required.

Hence, the first data to obtain before designing a transmission line are complete weather reports for the district, extending over a long term of years.

In the analytical discussions and formulæ to be given, the following are the definitions of the symbols used.

A = area of wire or cable (actual metal cross-section) in square inches.

c = weight, of conductor, per foot length.

D = deflection, of lowest point of wire from horizontal line drawn between the two supports, in feet.

d = diameter of wire, in inches.

F = tensile stress in wire, in pounds.

f = "stretch" or elongation of wire due to F, in feet.

h = horizontal force due to wind pressure, in pounds, per foot length of conductor.

i = weight of ice or snow on conductor, in pounds per foot length (see equation 135).

L = span, or horizontal distance between two points of support, in feet.

l = actual length of wire suspended between supports when stressed by forces acting on it, at some fixed temperature, assumed as standard.

l_0 = actual length of wire between supports when not under stress due to load or horizontal forces.

l_{at} = length of wire between supports at a given temperature when stressed.
M = modulus of elasticity of the material of which the conductor is composed.
S = sag, or vertical deflection of wire at lowest point, in feet.
u = coefficient of linear expansion of conductor per degree F.
v = total vertical force acting on conductor, in pounds per foot length.
W = total resultant force acting on conductor, in pounds per foot length.
Z = side swing, or horizontal deflection of wire in feet at its lowest point, due to wind pressure.

In the mathematical analysis of the sag, and corresponding stress under various conditions, it is customary to assume that the general form of the curve which the wires take is that of a parabola. As a matter of fact the curve is a catenary, but the difference between the catenary and the parabola is so small that actual conditions are fairly represented by the parabolic formulæ.

A second departure from the exact conditions is the use of approximate formulæ, only, in the computations. The length of the parabolic curve from the apex to a point x, y, is represented by the equation

$$l' = \tfrac{1}{2}\sqrt{4x^2 + y^2} + \frac{y^2}{4x}\left(\log_\epsilon \frac{2x + \sqrt{4x^2 + y^2}}{y}\right).$$

In practical computations and for y very great as compared with x, this reduces to $l' = y + \frac{2x^2}{3y}$. To derive this, values of $\frac{x}{y}$ to the fourth and higher powers are discarded as negligible. This simplifies the calculations, and is justified because the assumptions as to wind pressures and ice loading, which are the starting points, are, themselves, the crudest of approximations, and only inexperienced engineers will attempt to laboriously apply rigorous mathematical methods to conditions that are fundamentally inexact.

The vertex of the parabola, formed by a suspended wire, is at its point of greatest deflection. This point is in the middle of the span when the supports, or insulators, are at the same height. Hence, the total length of the wire in the span is the sum of the two branches of a parabola which form the span.

Substituting $\frac{L}{2}$ for y, and D for X, in the formula, the half length of the span becomes

$$\frac{l}{2} = \frac{L}{2} + \frac{2D^2}{\frac{3L}{2}}$$

or

$$l = L + \frac{8D^2}{3L}$$

The wire will deflect vertically only, due to its weight and the weight of ice or snow on it, if any be present, unless there be an appreciable wind pressure to set up a uniformly distributed, horizontal force, in which case the wire will deflect downward and to one side as indicated in Fig. 161. The total deflection is $D = ab$ in the figure, and it is due to the resultant of the vertical and horizontal forces. If v be the vertical force due to gravity, and h be the horizontal force due to wind pressure, the total resultant force is $\sqrt{v^2 + h^2} = W$. (122)

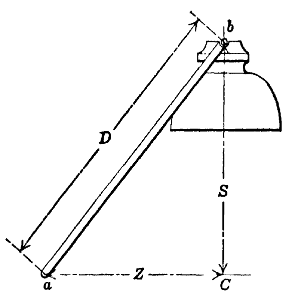


FIG. 161.—Deflection of wires.

The sag, $S = \frac{vD}{W}$. (123) This is bC in the figure.

The "swing," $Z = \frac{hD}{W}$. (124) This is aC in the figure.

When there is no horizontal force, $h = o$ and $W = v$. so that $S = D$ and $Z = o$.

Equations for supports having same height.—

$$D = \frac{WL^2}{8F} \tag{125}$$

$$l = L + \frac{8D^2}{3L} \tag{126}$$

whence

$$l_0 = l - f.f = \frac{(l - f)F}{AM}$$

$$l_0 = \frac{lAM}{AM + F}. \tag{127}$$

$$l = l_0 + \frac{l_0F}{AM}. \tag{128}$$

Or, for unit cross-section and unit weight, per foot

$$l = l_0 + \frac{l_0 F}{M}. \tag{129}$$

If the unstressed length of wire for some other temperature be required, as at a temperature t_1, the length l_1 at this temperature will be

$$l_1 = l_0 \pm l_0 \beta u \tag{130}$$

in which

β = change of temperature in number of degrees F.
u = coefficient of expansion per degree, F.
Sign + is used when temperature increases.
Sign − is used when temperature decreases.

In general, $\beta = t_0 - t_1$ for decrease in temperature, and $t_1 - t_0$ for increase in temperature, when the values of t_1 and t_0 are both above or below zero. If one of the temperatures is above and the other below zero, then $\beta = t_1 + t_0$.

If the sag, or deflection, and stress for this same length of wire at some other temperature, t_1, is required, a formula is derived from which they may be computed.[1] It is, however, so complex and involved, that a trial and error method is simpler, easier and, therefore, preferable.

Take the unstressed length of wire, l_0, at the first temperature. Find the change in the unstressed length due to the change in temperature, calling the unstressed length at the new temperature l_1. Assume a new value for F_1 and compute the stressed length of the wire and the deflection, D_1. Having the value of D_1, compute the actual stress in the wire.

If this finally computed value of F is approximately the same as the assumed value F_1, the assumption is correct. If it differs appreciably from F_1, the difference will indicate, very closely, what F_1 should be. A second assumption of F_1 must then be made, and the quantities again computed. By one or two trials the actual values of F and D may be found.

[1] Formula is

$$D = \sqrt[3]{\frac{G}{2} + \sqrt{\frac{G^2}{4} - \frac{p^3}{9}}} + \sqrt[3]{\frac{G}{2} - \sqrt{\frac{G^2}{4} - \frac{p^3}{9}}}$$

$$G = \frac{3WL^3}{64}K, \qquad p = \frac{3L}{8}(KaM - L), \qquad K = \frac{L + \frac{8D_0^2}{3L}}{AM + \frac{WL^2}{8D_0}}[1 - u(t_1 - t_0)]$$

a, M, L, D_0, W, t, and t_0 as before given.

If D_1 be the new value of the deflection at a different temperature and loading,

$$l_1 = L + \frac{8D_1^2}{3L} \tag{131}$$

and

$$D_1 = \sqrt{\frac{(l_1 - L)3L}{8}} \tag{132}$$

$$F_1 = \frac{WL^2}{8D_1}. \tag{133}$$

Also,

$$f_1 = \frac{l_0 F_1}{AM} \tag{134}$$

After computing the value of F_1 from formula 133, and using the value of D_1 obtained from the assumption of a preliminary value of F_1, the result will be very close to the actual value of F. By taking the value so found as the assumed value of F_1 for the second trial, and recomputing, the value found the second time will be the true value of F, or so close to it that there will be no necessity for a third repetition of the process. For exact results, the computations have to be repeated until the calculated value of F is exactly the same as the previously assumed value. Great accuracy is unnecessary, however, as F and D finally depend on the tension exerted when the workmen string the wires. The inaccuracies of laborers, the friction of the cables in the insulator grooves (in the case of pin-type insulators), the temperature variations that may occur between thermometer readings by the erecting foreman, and other causes present in practical construction, make it commercially impossible to get the actual values of F and D closer to the theoretical design than about 3 per cent. Hence, if values of F, as computed, are within 3 per cent. of the preliminary assumed values, the results are as accurate as can be expected to obtain in the line itself. Of course, the stress in the wire must never exceed that which will elongate the metal beyond its elastic limit.

For computation of the weight of ice on wires

$i = 1.24\, \alpha\, (d + \alpha)$ in pounds per foot length (135).
d = diameter of wire, in inches.
α = thickness of layer of ice, in inches.

The following table gives the physical constants necessary

for use in computing sag and stresses, for copper, aluminum and steel.

TABLE 25.—PHYSICAL CONSTANTS OF WIRES AND CABLES[1]

Name of constants	Copper	Aluminum	Steel
Tensile strength, pounds per square inch	60,000 to 65,000	25,000 to 50,000	80,000 to 100,000
Elastic limit, pounds per square inch	30,000 to 35,000	11,000 to 14,000	35,000 to 50,000
Modulus of elasticity, pounds per square inch	12×10^6 to 16×10^6	8×10^6 to 10×10^6	22×10^6 to 28×10^6
Coefficient linear expansion per degree F. $= u$	9.6×10^{-6}	12.8×10^{-6}	6.6×10^{-6}
Weight per foot, 1,000,000 cir. mils.	3.09 lb.	0.92 lb.	2.67 lb.

The higher values of the modulus of elasticity are for solid wires, the lower for cables.

As an example, to illustrate the method of making the computations, consider a line having the following characteristics.

L = span = 600 ft.
Wire, aluminum; size, 0000 B. & S. gauge.
c = weight per foot = 0.195 lb.
d = diameter = 0.52 in.
Maximum allowable stress = 14,000 lb. per square inch.
A = area of cross-section of wire (net) = 0.1662 sq. in.
$F_{max} = 0.1662 \times 14{,}000 = 2330$ lb.

Assume ice loading to be ½ in. thick at temperature = 10°F.
i = weight of ice, per foot $= 1.24 \times 0.5\,(0.52 + 0.5) = 0.632$ lb. per foot.

Take wind pressure = 10 lb. per square foot. (The wind pressure acting against a cylindrical surface is approximately two-thirds that which the same wind velocity would produce acting against a flat surface having an equal area. The formula for wind pressure against a wire, in pounds per foot length, is

$P = 0.00022V^2d$. V being the velocity in miles per hour.)

Projected area of 1 ft. length of wire $= \dfrac{d + 2\alpha}{12} = \dfrac{1.52}{12} = 0.1251$ sq. ft.

[1] For constants of bi-metallic wires, see p. 163.

h = horizontal force = $0.1251 \times 10 = 1.251$ lb. per foot length.

v = vertical force = $i + c = 0.632 + 0.195 = 0.827$ lb. per foot length.

W = total force = $\sqrt{v^2 + h^2} = \sqrt{(0.827)^2 + (1.251)^2} = 1.5$ lb. per foot length.

$$D = \frac{1.5 \times (600)^2}{8 \times 2330} = 28.43 \text{ ft.}$$

$$S = \frac{28.43 \times 0.827}{1.5} = 15.67 \text{ ft.}$$

$$Z = \frac{1.251}{1.5} \times 28.43 = 23.7 \text{ ft.}$$

l = length of wire = $600 + \dfrac{8 \times (28.43)^2}{3 \times 600} = 603.587$ ft. at temperature of 10°F (formula 131).

Take M as a little below the mean value of extremes given in table 25, or as 8×10^6.

The unstressed length of wire is, from equation (127)

$$l_0 = \frac{603.587 \times 0.1662 \times 8 \times 10^6}{0.1662 \times 8 \times 10^6 + 2330} = 602.531 \text{ ft.}$$

That is, the unstressed length of the wire at 10°F. is, actually, 602.531 ft., while in its elongated or "stretched" condition it is 603.587 ft. The amount of elongation, due to load stress is, therefore, 1.056 ft.

Take next the condition of minimum temperature, equal to 20°F. below zero.

Then the unstressed length of the wire changes to

$$l_1 = 602.531 - 602.531 \times 12.8 \times 10^{-6} \times [10 - (-20)].$$

Reduction in length, due to lowering of temperature 30°, is

$$602.531 \times 0.000384 = 0.231 \text{ ft.}$$

Hence, at -20°F., $l_1 = 602.531 - 0.231 = 602.3$ ft.
Assume as a trial value, $F_1 = 273$ lb.

Then elongation due to stress = $\dfrac{602.3 \times 273}{8 \times 10^6 \times 0.1662} = 0.1235$ ft.

Hence, total length of stressed wire at new load and temperature is

$$l_{at} = 602.3 + 0.1236 = 602.4236 \text{ ft.}$$

and, by formula 132.

$$D_1 = \sqrt{\frac{(602.4236 - 600) \times 3 \times 600}{8}} = 23.35 \text{ ft.}$$

Using this value of D_1, the stress would be

$$F_1 = \frac{0.195 \times (600)^2}{8 \times 23.35} = 375 \text{ lb. (approximately).}$$

Recompute as before, using this value for F.
Elongation of wire due to 375-lb. stress =

$$\frac{602.3 \times 375}{8 \times 10^6 \times 0.1662} = 0.17 \text{ ft.}$$

Hence total length of wire for new value of $F = 602.3 + 0.17 = 602.47$.

$$D = \sqrt{\frac{(602.47 - 600) \times 3 \times 600}{8}} = 23.57 \text{ ft.}$$

Using this value of D and solving for the stress

$$F = \frac{0.195 \times (600)^2}{8 \times 23.57} = 372 \text{ lb.}$$

This is within 3 lb., or 1 per cent., of the last assumed value and no further computation is necessary. The exact value of F by repeated computation, is 372.6 lb.

By taking various temperatures and assuming that there is neither ice, nor wind load, a table is computed as follows:

Basis—Maximum loading at 10°F. taken as ½ in. ice coating and wind pressure of 10 lb. per square foot. All other values for loading due to weight of wire only.

TABLE 26.—SAG, TENSION AND LENGTH OF 0000 ALUMINUM CABLE FOR 600-FOOT SPAN

Temperature, Fahrenheit	Length of cable, feet		F Tensile stress in cable, pounds	D Sag, feet
	l_0 = Unstressed	l = Stressed		
20	602.6084	602.7716	351	24.99
30	602.6855	602.8345	347	25.25
40	602.7626	602.9110	343	25.59
50	602.8397	602.9869	338	25.92
60	602.9168	603.0685	334	26.26
70	602.9939	603.1429	330	26.59
80	603.0710	603.2160	326	26.90
90	603.1481	603.2393	322	27.22
100	603.2253	603.3700	318	27.54
110	603.3023	603.4470	315	27.85

With this table, based on the conditions assumed, the erecting gang can pull the cable to the proper degree of tension, and give the corresponding sag, for any temperature of the surrounding air. No transmission line can be properly erected without the use of a spring balance to measure the tension on the wire before tying it in place, and a thermometer to determine just how great the tension should be. Measuring by deflection, or sag, is inaccurate and unsatisfactory.

For erecting purposes, a table, similar to that just preceding, must be prepared, always starting with the condition of maximum stress to fix the length of wire between supports.

It is to be noted that for cables of a given material, with a fixed stress per square inch, the sag and length of wire between spans will be the same for all sizes of cable. Hence, a table for one size of cable is easily transposed to values for some other size by merely multiplying the values of F in the first table by the ratio of the cross-section of the second cable to the first. For instance, if a table of values of F for No. 0 B. & S. cable at various temperatures be desired, and a table be available for No. 0000, of the same metal, the values in the second table, multiplied by $\frac{105,625}{211,600}$, or 0.5, will give the corresponding values of F for the No. 0 cable.

This, however, applies only to tables in which the maximum stresses are based on no ice load. If the highest stress and corresponding deflection are based on simultaneous ice and wind loads, the relation between all sizes of cable no longer holds. This is obvious from the fact that part of the load varies as the square of the diameter of the wire, and part as its first power. In such cases, the unit stresses can not be used for general application to all sizes of wires, but each size must be individually computed. At the end of this chapter are tables giving the values of the horizontal forces, h, and the vertical forces, v, and the resultant force $W = \sqrt{h^2 + v^2}$ for various sizes of cables of aluminum, copper and steel, unloaded, and for various ice loadings.

If the sag for a given cable under certain assumed conditions for one length of span, be known, the sag for any other span will be

$$S_1 = S\left(\frac{L_1}{L}\right)^2 \tag{136}$$

in which

S_1 = sag for new length of span.
L_1 = length of new span.
S = known sag for span of length, L.

Formulæ for Supports of Unequal Height.—The foregoing discussion and formulæ, apply only to conditions where insulators on the poles, or towers, have substantially the same elevation. Where the two supports, between which the span of cable is stretched, are at different elevations, the formulæ must be modified to cover this condition.

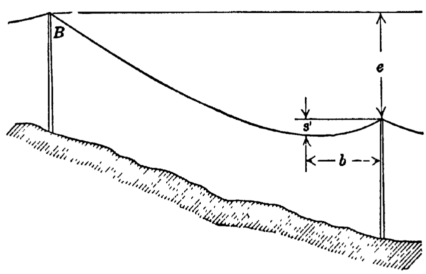


FIG. 162.—Deflection of wires on supports of unequal height.

Consider Fig. 162, where the support B is higher than A. The vertical curve the wire will assume is indicated in the figure. The lowest point of the line is nearer to A than to B.

Let e represent the difference in elevation of the two points of support, in feet.

S^1 = vertical deflection, or sag, below the elevation of the lower support, in feet.

l^1 = length of wire in the span.

b = distance of lowest point in the line from the lower support.

Then

$$F = \frac{WL^2}{8S^1} \tag{137}$$

and

$$S^1 = S\left(1 - \frac{e}{4S}\right)^2 \tag{138}$$

S being the value of the sag for supports of equal height with same span.

$$l^1 = L + \left(\frac{8D^2}{3L} + \frac{e^2}{2L}\right) \tag{139}$$

D being the value of the total deflection under the same set of conditions, for the wire strung between two supports of equal height.

$$b = \frac{L}{2}\left(1 - \frac{e}{4S}\right). \tag{140}$$

Sag and Stresses for Suspension Insulator Lines.—The foregoing analyses and formulæ are for fixed and rigid line supports—that is, the span L is practically constant under all conditions of stress up to the limit of rupture of insulators or crossarms.

With suspension insulators, any difference in stress between adjacent spans is compensated for by a movement of the insulator group in one direction or the other, thereby varying the actual length of span of the two adjacent sections of cable.

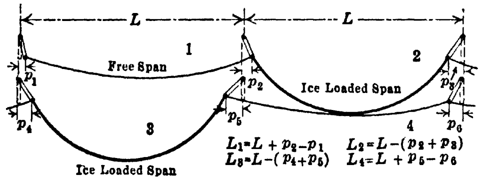


FIG. 163.—Movement of suspension insulators and differences in sag of unequally loaded spans.

This condition is more favorable to the preservation of the line and prevention of failure than that which obtains with rigid supports. It, however, has the objection that the sway, or "swing," of the lines is considerably greater than when placed on pin-supported insulators, and the sag, for one or two sections, may become excessive under certain differences of loading, as will be set forth later.

Consider Fig. 163. If the line has been ice loaded, the spans do not clear themselves of the ice at the same time, but some spans will become cleared while others are loaded. If one line be located above another, either in the same vertical plane or in separate vertical planes, very near each other, the clearances between the two lines may be greatly reduced, and, in extreme cases, the two lines may come in contact with each other.

Assume in the figure that span No. 1 of the upper line, and No. 4 of the lower line are unloaded, while spans 2 and 3 are ice loaded. The suspension insulator group of the upper line will swing toward the right, reducing the sag of span No. 1 and increasing that of span No. 2. On the lower line, span No. 3

will have an excessive sag, while span No. 4 will be pulled up tightly and will have less than the normal sag. This set of conditions makes spans No. 2 and No. 4 approach each other, diminishing the clearance between them. Hence, it becomes necessary to compute the sags in the different sections of a line hung from suspension insulators when partly ice loaded and partly unloaded.

Referring to Fig. 163, the normal length of each span is equal to L, as shown. This length of span is changed by the deflection of the insulator group, due to the loading on span No. 2, so that the length of span of No. 1, or $L_1 = L + p$, and the length of span No. 2, or $L_2 = L - p$, p being the algebraic sum of the horizontal distances of the deflection of the lower end of the insulator groups. Since the respective weights, per foot, of the two spans of wire are known, the deflection of each span may be easily computed if p and F are known. The algebraic solution for the value of p, however, results in an equation of the fourth degree, and the formula is too long and complex for practical use. Instead, an approximate formula is given herewith which is based on rejecting all quantities having values near unity and with exponents greater than 2.

This approximate formula is used to fix a preliminary value of p for a trial and error computation, and, as will be presently shown, the results obtained by its use are very close to the exact value so that seldom is a second computation necessary. Any assumption of ice loading and of coincident temperature, are assumptions only, and the expenditure of time and mental effort to make exact computations based on such an inexact foundation, is clearly unwarranted. All that can be done, in any case, is to approximate a final extreme condition of sag and stress, with a reasonable factor of safety to cover the errors arising from the human inability to predict the actual, maximum conditions of stress and loading that the line will be subjected to.

The approximate formula for the value of p is

$$p = (l_{at} - L)\frac{L}{l_{at}}\left(\frac{\phi^2 - 1}{\phi^2 + 1}\right) \tag{141}$$

in which

L = normal span, in feet.

l_{at} = stressed length of cable in the normal span at the assumed temperature.

$\phi = \frac{w_2}{w_1}$; w_1 and w_2 being, respectively, the weights per foot length of the cables in span No. 1 and adjacent span No. 2, including ice loading.

The tension in the cable in each span is practically the same, that is, $F_1 = F_2$. In reality, $F_1 = F_2 - k$, in which k is the horizontal force necessary to deflect the insulator group, but this force is usually negligible.

If E = weight of group, Q = its length, and k = horizontal force applied at the lower end of the insulator group:

$$k = \frac{Ep}{2\sqrt{Q^2 - p^2}}.^{1} \tag{142}$$

Since insulator groups weigh around 60 lb. the value of k for values of p, up to $0.4Q$ (*i.e.*, deflection = 0.4 length of insulator string) is

$$\frac{60}{2} \frac{0.4Q}{\sqrt{Q^2 - 0.16Q^2}} = \frac{30 \times 0.4Q}{\sqrt{0.984Q^2}} = 12.12 \text{ lb.}$$

which is negligible compared with the stresses in the cables produced by sag and loading.

To find the value of l_{at}, it is necessary to make a preliminary assumption of the value of F_1 in order to determine the elongation of the cable. Following is the procedure to determine the sags and stresses.

Assume the stresses in the wires to be, approximately, half the maximum stress allowed under the worst conditions. On this assumption, find the length of wire (stressed) in a span from the formula

$$l_{at} = l_o + l_o u\beta + \frac{l_o F}{M}. \tag{143}$$

(See formulæ 128 and 130.)

Next, compute the movement of the insulator toward the more heavily loaded span, from formula 141 for the value of p.

[1] **Derivation of This Formula is as Follows.**—Refer to Fig. 164. If group is swung to the left a distance = p, the horizontal force k = weight of group acting through its center of gravity at G, and having a displacement toward the left $= \frac{p}{2} \cdot k = \frac{E \tan \theta}{2}$, θ being the angle the axis of the insulator string makes with the vertical. From the figure it is clear that $\tan \theta = \frac{p}{\sqrt{Q^2 - p^2}}$. Hence, $k = \frac{Ep}{2\sqrt{Q^2 - p^2}}$.

Then the span for the ice-loaded section will be $L - p$, while the span for the unloaded section will be $L + p$.

With these values of F_1 and p, compute the stress in both the loaded and unloaded sections, *i.e.*, F_1 and F_2, in the manner previously indicated (see formula 133). If the two stresses thus computed are approximately equal—say within 5 per cent. of each other—the values assumed are both correct. If the stresses differ considerably, add the values of F_1 and F_2 as found and take half this sum as the nearer value of F. Then compute a new value of l_{at} and change slightly the value of p, making it greater if the stress in the loaded span exceeds that in the unloaded one.

After making the new assumptions, recompute the values of F_1 and F_2 as before. Proceed in this manner until the values of F_1 and F_2 are within 5 per cent. of each other. Then, using the values of $L_1 = L - p$, in formula (132), calculate the sag of the loaded wire. The result will be close enough to the actual value for all practical purposes.

It is to be noted that extremely small changes in the value of p will make comparatively great changes in the values of F. Also, whenever p begins to exceed 0.4 Q, the weight of the insulator group becomes a factor and the stresses in the two spans are not approximately equal, Q being the length in feet of the insulator group, measured from the point of suspension to the cable.

As an example, consider a 0000 B. & S. gauge, aluminum cable, hung from suspension insulators, with a normal span of 600 ft. This condition is chosen because a line having these constants has become familiar from preceding examples.

It was found that the unstressed length of wire, in a 600-ft. span, at $-20°$F. (based on ice and wind load as maximum conditions of stress) was 602.3 ft. Call this l_0.

For the condition of melting ice on wires, the temperature should be taken at 34°F. Note that the temperature of the wire is higher than that of the ice that surrounds it, due to energy liberated from surface of the wire in the form of heat.

The maximum stress in the wire was found to be 2330 lb., or 14,000 lb. per square inch (see previous example). Taking less than half of this, the trial value assumed for F is 6000 lb. per square inch.

Then

$$l_{at} = l_0 + l_0 u\beta + \frac{l_0 F}{M}$$

$$u = 12.8 \times 10^{-6} \qquad \beta = 20 + 34 = 54.$$

Hence

$$l_{at} = 602.3 + 602.3 \times 12.8 \times 10^{-6} \times 54 + \frac{602.3 \times 6000}{8 \times 10^6}$$

$$= 603.1735 \text{ ft.}$$

$w_1 = 0.195$ lb. per foot. $\quad w_2 = 0.823$ lb. per foot.

$$\frac{w_2}{w_1} = \phi = \frac{0.823}{0.195} = 4.22$$

$$p = (603.1735 - 600)\frac{600}{603.1735}\left(\frac{(4.22)^2 - 1}{(4.22)^2 + 1}\right) = 2.82 \text{ ft.}$$

Then the distance between supports of the unloaded span, is

$$L_1 = 600 + 2.82 = 602.82 \text{ ft.}$$

and the distance between supports of the loaded span, is

$$L_2 = 600 - 2.82 = 597.18 \text{ ft.}$$

Taking first the unloaded span, from formula 132

$$D_1 = \sqrt{(603.1735 - 602.82)\frac{3 \times 602.82}{8}} = 8.94 \text{ ft.}$$

From formula 133

$$F_1 = \frac{0.195 \times (602.82)^2}{8 \times 8.94} = 991.16, \text{ lbs.}$$

$$\text{Unit stress} = \frac{F_1}{A} = \frac{991}{0.1662} = 5962 \text{ lb. per square inch.}$$

(0.1662 is the area of a No. 0000 cable, in square inches.)
This value of F_1 is so near that assumed, that the value of l_{at} may be accepted as correct.

For the loaded span,

$$D_2 = \sqrt{(603.1735 - 597.18)\frac{3 \times 597.18}{8}} = 36.63 \text{ ft.}$$

and

$$F_2 = \frac{0.823 \times (597.28)^2}{8 \times 36.63} = 1001 \text{ lb.}$$

$$\text{Stress per square inch} = \frac{1001}{0.1662} = 6023 \text{ lb.}$$

This value is so near that found for F_1 that the deflection of the ice-loaded side may be taken as 36.63 ft. under the assumed loading and temperature.

Clearly, if the several spans have a minimum sag of about 23.5 ft., the spans No. 2 and 4 have approached closer than normal by $(23.5 - 8.94) + (36.63 - 23.5) = 27.69$ ft., or the

horizontal planes, through the lowest points of the cables, are 27.69 ft. closer together than they normally are.

Clearance Between Line and Ground.—With a knowledge of the maximum sag in the wires and the location of the lowest points of the deflection curve, the heights of the poles or towers can be fixed. These must have a height such that the lowest points on the line between supports will clear the ground, by a predetermined amount.

Just what these clearances should be is subject to the views of the designer, and they vary also with the character of the locality through which the line runs, and that of the line itself.

For the usual high-tension line, the minimum clearance should be 20 ft., and 35 ft. over roadways. Where the line passes over structures of any kind a clearance of 15 to 18 ft. should be allowed.

Side Swing of Suspension Insulators.—In any system of horizontal and vertical forces, such as indicated in Fig. 164, the position which a body G, free to oscillate about a pivot O, will take will be such that the tangent of the angle θ will equal $\frac{v}{h}$.

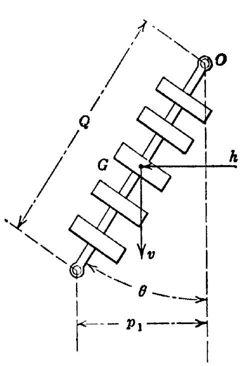


FIG. 164.—"Swing" of suspension insulators.

In a transmission line, if v and h are, respectively, the vertical and horizontal forces, either per foot length, or total over a whole span, $\tan \theta = \frac{v}{h}$, and the deflection, p_1, $= Q \sin \theta$, Q being the length of the insulator group from the cable to the point of support.

$$p_1 = \frac{Qh}{\sqrt{h^2 + v^2}} \tag{144}$$

Where the spans are carried on supports of unequal height, and the spans are of unequal length, these formulæ must be modified.

Referring to Fig. 165, 1, 2, and 3 are three supports carrying suspension insulators, and between them are strung spans a and b. The portion of each span supported by insulator No. 2 is that part lying between the lowest point of the wire and the insulator, and the total length of wire supported by the insulator is that length included between the two lowest portions of the

adjacent spans, marked d_1 and d_2 in the figure, their sum being n. Hence, the vertical force due to gravity is $v(d_1 + d_2)$, in which v = weight per foot of the wire plus ice load, if any.

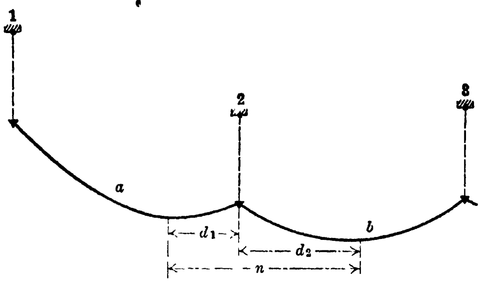


FIG. 165.—Loading of suspension insulators.

The wind pressure acts, however, uniformly, over the whole length of the two spans, so that the total horizontal force is $h\left(\frac{a}{2} + \frac{b}{2}\right)$ in which a and b are the lengths, respectively, of spans a and b.

Placing $\frac{a}{2} + \frac{b}{2} = m$, the general formula, for the side deflection of suspension insulators becomes,

$$\tan \theta = \frac{v(d_1 + d_2)}{h\left(\frac{a}{2} + \frac{b}{2}\right)} = \frac{vn}{hm} \tag{145}$$

and

$$p_1 = Q \sin \theta. \tag{146}$$

The weight of the insulator is not included in these formulæ, being negligible in practice.

The total side swing of the wires is equal to the side swing as computed for rigid insulators, plus p_1.

Method of Locating Supports.—The positions of the poles, or towers, for a transmission line can be most conveniently and accurately determined by means of a template, which is moved along the profile map of the route of the line, from point to point, and the necessary locations fixed graphically.

Cut out of a piece of celluloid, a template shaped like the figure *ABCXD*, the curve *BCX* being that of the cable when under its maximum deflection (see Fig. 166). The form of this curve is determined by the equation $Y = \left(\frac{4S}{L^2}\right) X^2$ in which S = maximum

sag at the middle point, in feet. Trace on the celluloid two other curves exactly similar to the first one. The uppermost curve, *EFG*, is located above the lowermost curve a distance such that a vertical drawn from one curve to the other represents, to scale, the height of the support above the ground. The intermediate curve, *KLN*, is located below curve *EFG* a distance such that the length of a vertical drawn from one curve to the other represents, to scale, the minimum allowable clearance between the ground and the line. Draw also the vertical axis *YY*. Obviously, the scale to which these curves are plotted is the same as that to which the profile of the line is drawn.

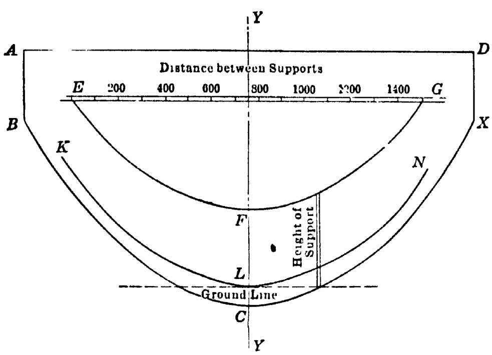


FIG. 166.—Template for locating transmission-line supports.

To use this template, place it over the profile with the axis *YY* vertical, and the intermediate curve, *KLN*, tangent to the line of the profile. Then, the intersection of the lowermost curve *BCX* with the line of the profile will be the proper location for the line supports. This condition is true for any profile, straight or sloping if *YY* be kept always vertical.

Starting at one end of the line, the first pair of supports is fixed; the template moved along so that one of the intersections of the bottom curve with the profile coincides with one of the previously located supports; the position of the third support fixed, and so on over the length of the profile.

A good heavy piece of tracing cloth, with all three of the curves traced on it, may be used instead of celluloid, and the locations marked with needle point punctures made through the cloth and the profile paper.

TABLE 27.—LOADING TABLES[1]

Copper wire—stranded

Cir. mils and A.W.G	Diam., in.	Area, sq. in	Hard drawn		Soft drawn		Load per lin foot, vertical			Load per lin. foot, horizontal			Max. load per lin. foot, plane of resultant			EA	
			Ultimate tension, lb	Allow. tension	Ultimate tension, lb	Allow. tension	Dead	Dead + ½ in. ice	Dead + ¾ in ice	15.0 lb p sq. ft	8.0 lb. p sq. ft ½ in ice	11.0 lb p sq ft ¾ in. ice	Class A load'g	Class B load'g	Class C load'g	E(hard drawn) 16,000,000	E(annealed) 12,000,000
500,000	0.819	0.3924	23,540	11,750	13,340	6,650	1.525	2.345	2.989	1.024	1.213	2.126	1.837	2.640	3.668	6,278,400	4,708,800
350,000	0.679	0.2750	16,500	8,250	9,350	4,650	1.068	1.801	2.401	0.849	1.119	1.997	1.364	2.120	3.123	4,400,000	3,300,000
0,000	0.530	0.1662	9,970	5,000	5,650	2,800	0.645	1.286	1.831	0.663	1.020	1.861	0.925	1.641	2.611	2,659,200	1,994,400
000	0.470	0.1318	7,910	3,950	4,480	2,250	0.513	1.116	1.651	0.588	0.980	1.806	0.780	1.485	2.446	2,108,800	1,581,600
00	0.420	0.1045	6,270	3,150	3,555	1,750	0.406	0.978	1.498	0.525	0.947	1.760	0.664	1.361	2.311	1,672,000	1,254,000
0	0.375	0.0829	4,970	2,500	2,820	1,400	0.322	0.866	1.372	0.469	0.917	1.719	0.569	1.261	2.199	1,326,400	994,800
1	0.330	0.0657	3,940	1,950	2,235	1,100	0.255	0.771	1.263	0.413	0.887	1.678	0.485	1.175	2.100	1,051,200	788,400
2	0.291	0.0521	3,130	1,550	1,770	900	0.203	0.695	1.174	0.364	0.861	1.642	0.417	1.107	2.019	833,600	625,200
3	0.261	0.0413	2,480	1,250	1,405	700	0.160	0.633	1.103	0.326	0.841	1.614	0.363	1.053	1.955	660,800	495,600

Copper wire—solid

Cir. mils and A.W.G	Diam., in.	Area, sq. in	Hard drawn Ultimate tension, lb	Hard drawn Allow. tension	Soft drawn Ultimate tension, lb	Soft drawn Allow. tension	Dead	Dead + ½ in. ice	Dead + ¾ in ice	15.0 lb p sq. ft	8.0 lb. p sq. ft ½ in ice	11.0 lb p sq ft ¾ in. ice	Class A load'g	Class B load'g	Class C load'g	E(hard drawn) 16,000,000	E(annealed) 12,000,000
0,000	0.460	0.1662	8,310	4,150	5,650	2,800	0.641	1.238	1.770	0.575	0.973	1.797	0.861	1.575	2.522		
000	0.410	0.1318	6,590	3,300	4,480	2,250	0.509	1.074	1.591	0.512	0.940	1.750	0.722	1.427	2.365		
00	0.365	0.1045	5,220	2,600	3,555	1,750	0.403	0.940	1.443	0.456	0.910	1.709	0.608	1.309	2.237		
0	0.325	0.0829	4,560	2,300	2,820	1,400	0.320	0.833	1.323	0.406	0.883	1.673	0.517	1.214	2.133		
1	0.289	0.0657	3,740	1,850	2,235	1,100	0.253	0.744	1.223	0.362	0.860	1.640	0.442	1.137	2.046		
2	0.258	0.0521	3,120	1,550	1,770	900	0.202	0.673	1.142	0.322	0.838	1.611	0.380	1.075	1.975		
3	0.229	0.0413	2,480	1,250	1,405	700	0.159	0.613	1.073	0.287	0.820	1.585	0.328	1.024	1.914		
4	0.204	0.0328	1,960	1,000	1,115	550	0.126	0.564	1.016	0.255	0.803	1.567	0.284	0.981	1.863		
5	0.182	0.0260	1,560	800	885	450	0.100	0.524	0.969	0.227	0.788	1.542	0.248	0.946	1.821		
6	0.162	0.0206	1,240	600	700	350	0.079	0.491	0.930	0.203	0.775	1.524	0.218	0.917	1.785		

TABLE 28.—LOADING TABLES[1]

Aluminum wire—stranded

Cir. mils and A.W.G.	Diam., in.	Area, sq. in.	Hard drawn		Soft drawn		Load per lin foot, vertical			Load per lin. foot, horizontal			Max. load per lin. foot, plane of resultant			EA	
			Ultimate tension, lb.	Allow. tension	Ultimate tension, lb.	Allow. tension	Dead	Dead + ½ in. ice	Dead + ¾ in. ice	15.0 lb. p. sq ft.	8.0 lb. p sq ft. ½ in ice	11.0 lb. p. sq. ft. ¾ in. ice	Class A load'g	Class B load'g	Class C load'g	E(hard drawn) 16,000,000	E(annealed) 12,000,000
																9,000,000	
500,000	0.814	0.3924	9,025	4,500	......	. .	0.460	1.280	1.919	1.018	1.209	2.121	1.117	1.762	2.860	3,531,600	
350,000	0.679	0.2750	6,325	3,150	. . .	. .	0.322	1.055	1.655	0.849	1.119	1.997	0.908	1.538	2.594	2,475,000	
0,000	0.522	0.1662	3,820	1,900	. . ....	.	0.195	0.831	1.382	0.652	1.015	1.853	0.681	1.312	2.312	1,495,800	
000	0.464	0.1318	3,160	1,600	. . . .	. .	0.155	0.755	1.288	0.580	0.976	1.800	0.600	1.234	2.213	1,186,200	
00	0.414	0.1045	2,510	1,250	. . .	.	0.122	0.691	1.208	0.518	0.943	1.754	0.532	1.168	2.130	940,500	
0	0.368	0.0879	1,990	1,000	. .	.	0.097	0.637	1.140	0.460	0.912	1.712	0.470	1.112	2.057	746,100	
1	0.328	0.0657	1,575	800	. .	.	0.077	0.592	1.082	0.410	0.885	1.676	0.417	1.065	1.995	591,300	
2	0.291	0.0521	1,250	600	. .	.	0.061	0.533	1.032	0.364	0.861	1.642	0.368	1.023	1.939	468,900	
3	0.261	0.0413	990	500	.	. .	0.049	0.522	0.992	0.326	0.841	1.614	0.329	0.990	1.894	371,700	
4	0.231	0.0323	790	400	. .	. .	0.039	0.494	0.954	0.289	0.821	1.587	0.292	0.958	1.846	295,200	

NOTE: Class A loading = dead load + 15.0 lb. per sq ft wind pressure. E = modulus of elasticity, in.-lb.
Class B loading = dead load + 0.5 in ice + 8.0 lb wind pressure. A = conductor area.
Class C loading = dead load + 0.75 in ice + 11.0 lb wind pressure. EA = product of modulus of elasticity and conductor area.

[1] Report of the Joint Committee on Overhead Line Construction, N. E. L. A.

CHAPTER XII

LINE PROTECTION AND ACCESSORIES

Excessive potentials may be set up between the different wires of a transmission line, or between the wires and the earth, which may be sufficiently great to cause discharges over the insulators, shattering them, or the discharges may pass through the transformers and other apparatus, burning them and causing a shutdown of the plant. These destructive potentials may be produced either by the electromotive forces generated in the system itself, or by external electrical phenomena, such as charges from clouds, lightning discharge, and the like.

Obviously, the way to prevent the injurious effects of these excessive potentials is to provide paths between the wires, and from wires to ground, which are normally open and over which normal voltage can not cause current flow, but which higher and dangerous pressures will follow, and allow an equalization of these higher potential differences. Also, the flow through this path must be limited to excessive pressures only, and the instant they are neutralized, current flow must cease.

Devices which perform these functions are termed "lightning arresters," although only a small percentage of the discharges through them may proceed directly from lightning.

A second method of protecting the lines from high potentials between the wires and the ground is to keep the wires at or near the potential of the ground, by means of "ground wires," later to be described.

Practically all lightning arresters are made up of circuits between the wires and from the wires to the earth, these circuits being interrupted by gaps or openings, which are so adjusted that the normal line voltage can not jump across the gaps, and, under ordinary conditions of operation, there is no connection between the wires, nor from the earth to the wires. Abnormally high-potential differences across any of the gaps will cause the current to jump across them, thus producing an equalization of potential between the parts across which the high pressure

was set up. Since an arc, once started between two electrodes, may be maintained by a much lower pressure than that which caused the current to jump the gap, the line would be practically short-circuited after formation of the arc unless some automatic and instantaneous means be provided for extinguishing it, and stopping current flow across the gap.

Another essential feature is the means to compel any dangerous, suddenly produced pressures to follow the path across the gaps, and not to pass through the switches and transformers and jump to earth through the windings of the translating devices, or to jump from a wire to an insulator pin, thus shattering the insulator.

With these considerations it now becomes easy to understand the design of protective devices and the way in which they act under abnormal electrical stresses.

Horn-gap Arrester.—The earliest and perhaps most widely used protector is the "horn" arrester, in one of its many forms

Figure 167 is a diagram illustrating the general character of this arrester.

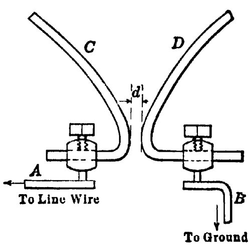
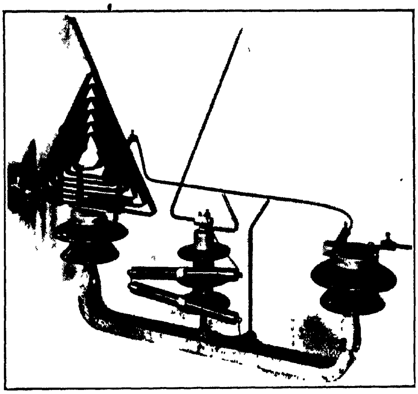


FIG. 167.—Horn gap.

The two metallic pieces *C*, *D* are bent in the form shown, and placed adjacent to each other, with a distance of separation, equal to *d*, at the lowest point. These pieces may have any cross-section, but are usually round, the diameter being about 0.32 in. (000 B. & S. gauge). As shown, the two portions gradually bend away from each other, until their distance apart at the top is many times greater than at the bottom. One piece is connected to one wire *A*, the other to the other wire *B*. An excessive pressure between the wires will cause current to jump across the gap at the narrowest point, the gap being adjusted so that, at some predetermined voltage, current can leap across it. Immediately, an arc is struck across the gap, but the arc instantly begins to rise, travelling upward between the two horns and thereby becomes longer and longer as the distance apart of the horns increases. A length of arc is soon reached which the normal voltage can not maintain, the arc dies out and current flow ceases.

This is the general theory of the horn-gap arrester. In practice, other corrective devices must be added to it to insure



Railway and Industrial Engineering Co.

FIG. 168.—Horn-gap lighting arrester and choke coil.

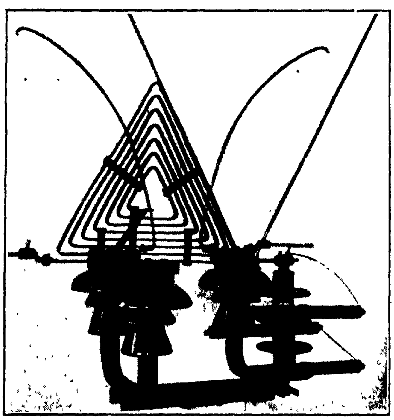


FIG. 169.—Horn-gap lighting arrester with choke coil.

its operation in time of need, and to definitely stop current flow immediately after discharge. The real difficulty with the horn-gap arrester is that if the gap be made short enough to give proper protection to the line, the arrangement is unstable. The gap is frequently jumped by the current and the arc is not

extinguished quickly enough to prevent surges and interference with the operation of synchronous apparatus.

Also, the arc may be sufficiently great, and persist so long, that the arrester itself is burned up, and the line left without protection. Hence, the necessity for auxiliary devices in connection with the horn gap.

Resistances of various kinds have been used in series with the horn connected to the ground. Figs. 168 and 169 show two horn arresters with one side of the horn formed into a triangular choke coil, and a resistance in the two tubes carried on the middle insulator. A second gap (on the right of the main gap in Fig. 168) is to take heavy surges which will jump across both gaps, in series, but the arc in the second gap will be extinguished by reason of its being shunted by the resistance, as explained in the discussion of "Multigap" arresters.

Electrolytic Arrester.—The most successful variant of the horn-type arrester is the so-called "electrolytic" or "aluminum" arrester.

Aluminum plates immersed in certain alkaline electrolytes—such as solutions of ammonium phosphate, sodium salts and the like,—and used as electrodes, have the peculiar property, that they set up a high resistance to the passage of electric current through the electrolyte when the plates are connected as anodes; that is, they resist the flow of current from plate to electrolyte.

The most important characteristic of the *aluminum cell* is its critical voltage, which depends upon the film of aluminum hydroxide formed on the surface of the aluminum plates. Up to a certain voltage the cell allows an exceedingly low current to flow, but at a higher voltage the current flow is limited only by the internal resistance of the cell, which is very low. A close analogy to this action is found in the well-known safety valve of the steam boiler, by which the steam is confined until the pressure rises above a given value, when it is released.

On the aluminum plates there are myriads of minute safety valves, so that, if the electric pressure rises above the critical voltage, the discharge takes place equally over the entire surface. It is important to distinguish between the valve action of this hydroxide film and the break-down of any dielectric substance such as mica, for example. The internal action of the cell closely resembles that of a storage battery on direct current, in

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which, up to about 2 volts per cell impressed, the storage battery gives an equal counter e.m.f. but above this value, the current that flows is limited only by the internal resistance of the cell.

The volt-ampere characteristics of an aluminum cell on alternating current, are shown in Fig. 170. The permanent critical voltage is between 335 and 360 volts.

When a cell is connected *permanently* to the circuit, two conditions of voltage are involved which may be distinguished as the temporary critical voltage, and the permanent critical voltage. For example, if the cell has 300 volts applied to it constantly, and the voltage is suddenly increased to, say, 325 volts, there will be a considerable rush of current until the film thickness has been increased to withstand the extra 25 volts; this usually requires several seconds. In this case 325 volts is the temporary

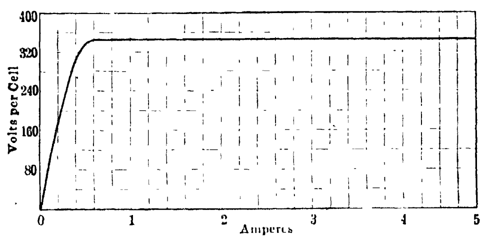


FIG. 170.—Volt-ampere characteristic curve of an aluminum cell on alternating current.

critical value of the cell. Similar action will occur at any potential up to about the permanent critical voltage, or the voltage at which the film can not further thicken and therefore allows a free flow of current.

If the voltage is again reduced to 300 the excess thickness of film will be gradually dissolved, and if it varies periodically between two values, each of which is less than the permanent critical value, the temporary critical voltage will be the higher value.

The number of cells for a circuit is so chosen that the maximum generator voltage per cell will be approximately 300 volts, or always less than the permanent critical voltage.

Another characteristic of the aluminum cell is the dissolution of a part of the film when the plates stand in the electrolyte and the cell is disconnected from the circuit. The film is composed

of two parts; one part is hard and insoluble, and apparently acts as a skeleton to hold the more soluble part. The action of the cell seems to indicate that the soluble part of the film is composed of gases in a liquid form. When a cell which has stood for some time disconnected, is re-connected to the circuit, there is a momentary rush of current which re-forms the part of the film which has dissolved. This current rush will have increasing values as the intervals of rest of the cell are made greater. If the cell has stood disconnected from the circuit for some time, especially in a warm climate, there is a possibility that the initial current rush will be sufficient to open the circuit breakers or oil switches. The current rush also raises the temperature of the cell, and if the temperature rise is great, it is injurious. When the cells are disconnected not longer than a day, however, the film dissolution and initial current rush are negligible.

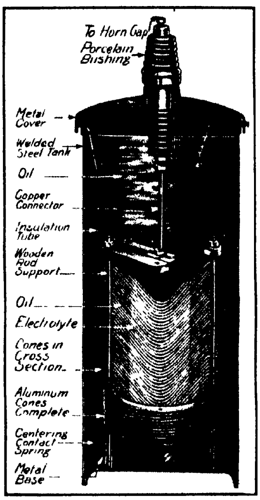


FIG. 171.—Cross-section of aluminum lightning arrester.

The form of the arrester varies according to the voltage. The

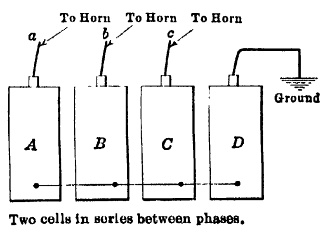


FIG. 172.—Connections of aluminum cells for lightning arresters.

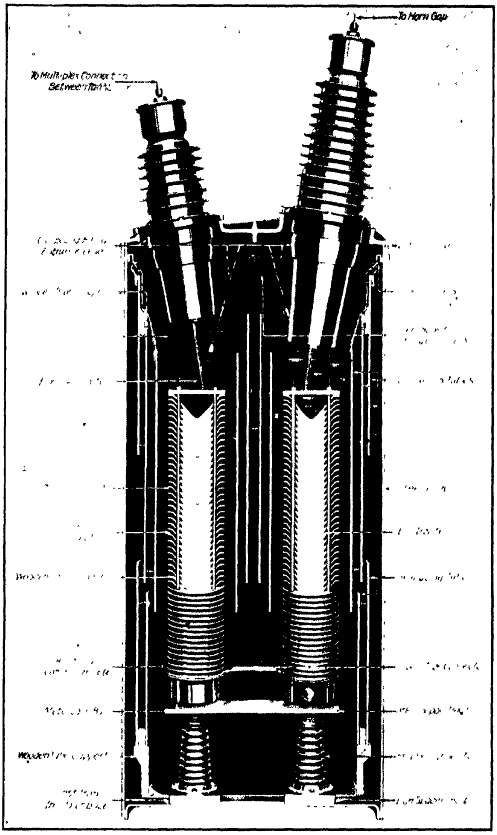
principal differences lie in the construction of the series horn gaps and in the grouping and spacing of the cells.

The cells consist of a series of concentric inverted cones, the number depending upon the voltage, placed one above the other with a vertical spacing of about 0.3 in. for arresters up to and including 27,000 volts and 0.42 in. for arresters above that voltage.

The electrolyte is poured into the cones and partly fills the space between adjacent ones. The stack of cones with the electrolyte between them is then immersed in a tank of oil. The

tanks are steel with welded seams and are provided with metal covers (Fig. 171).

The cones are insulated from each other except for the electrolyte. The oil improves this insulation as well as prevents the evaporation of the solution.



General Electric Co.

Fig. 173.—Section through tank of aluminum arrester, 110,000–150,000 volts.

A cylinder of insulating material concentric with the cone stack is placed between the latter and the steel tank. This improves the circulation of the oil and increases the insulation between the tank and the cone stack.

There is a stack for each phase, and an additional stack for the ground leg. The bases of the cone stacks are connected together in parallel.

The fourth stack is connected between the lead from the other three stacks and the ground, the object being to give the same protection between the line and ground as between line and line here, as shown in Fig. 172. This insures proper distribution of voltage in the cells during the conditions incident to an accidentally grounded phase. The fourth stack is called the ground leg of the arrester. Two of the stacks are connected directly to the line, each through a horn gap; the third is connected to the line through the transfer device and horn gap.

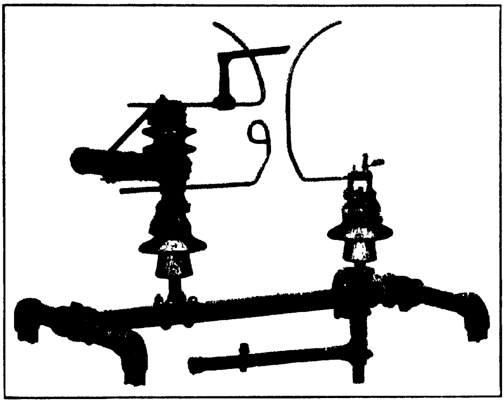


FIG. 174.—Horn gaps, with charging resistance for 12,500-volt aluminum arrester.

The fourth stack is connected to the ground through the transfer device.

For voltages above 75,000 the oval-tank type of construction is used. The construction is illustrated in Fig. 173. Owing to the large number of cones necessary for the higher voltages, the cone stacks would become unwieldy on account of their extreme height if the same construction as that for the lower voltage arrester were used. In the oval-tank arrester, the cones for each phase are put in two separate stacks which are connected in series. The stacks are insulated from the base of the tank and the tanks are grounded. The advantages gained from the standpoint of safety in having a grounded tank for these higher

voltages, are obvious. Barriers are used between the cone stacks and between the cone stacks and tank.

The cells are not designed to be connected permanently between the line and the ground. A horn gap, adjusted for a voltage greater than the line potential is inserted in series with each cell, and prevents them from being subjected continuously to the line voltage. In this way leakage is prevented at normal voltage and longer life is insured for the aluminum cones.

The horn gaps placed between the aluminum cells and the line serve a triple function.

First. As fixed gaps in series with the cells, they prevent the arresters from being subjected continually to the normal line voltage, which would result, ultimately, in overheating the cells.

Second. They act as disconnecting switches to disconnect the arrester from the line for repairs, inspection, etc.

Third. They can be used as connecting switches for daily testing. The gaps are designed so that they may be closed for a few seconds each day, and thus, keep the film in normal condition.

The closing of the horn gaps for charging, is effected by a rotating shaft of insulating material carrying three metallic projections, which, when the shaft is rotated, bridge the three gaps and allow the necessary charging current to flow through the cells. The disconnecting feature is provided with separate detachable fuses. The horn gaps are mounted on a pipe framework (see Fig. 174).

The charging switch used with arresters above 27,000 volts, has one of the supporting pins of one of the revolving insulators extended to a point within reach of the operator, and is fitted with an operating lever and latch. The movable insulators are all mechanically joined, so that by turning this lever all three horns are moved.

All horn gaps have resistances through which the arresters are charged.

The charging operation is as follows: First, the horn gaps of the arresters are closed for 5 sec. and opened again to normal position, thus charging the cells of the three line stacks. Second, with the horn gaps still in normal position, the position of the transfer device is reversed and the horn gaps are again closed for 5 sec. and returned to the normal position. The complete charging operation takes but a few seconds.

The object of the transfer device is to provide a means for interchanging the ground stack with one of the line stacks of

cones during the charging operation so that the films of all the cells will be formed to the same thickness.

The charging resistances are arranged to provide selective discharge paths to the cells. These paths consist of a main gap and an auxiliary gap, with a low resistance in series with the latter and in parallel with the main gap, as shown in Fig. 174.

The horns of the auxiliary gap are set closer together than those of the main gap and they are fitted with a charging contact which, at times of charging, bridges the auxiliary gap and charges the cells through the resistances.

In the normal operation of the arrester this arrangement of horns introduces selective paths for the discharge of lightning or other forms of potential surges. One path consists of a small auxiliary gap, a low resistance, and the aluminum cells; the other path consists only of the main gap and the aluminum cells. All discharges will first spark across the auxiliary gap and pass to ground through the resistance and the cells. If, however, the quantity of the discharge is too great to be dissipated through this path, the discharge automatically shunts to the main gap in which it is not impeded by the resistance. The resistance is of low value and, consequently, all but the heaviest discharges are taken care of by this auxiliary path.

In very warm climates it is necessary to take special precaution to keep the cells cool. At a temperature above 120°F., the hydroxide film can not be maintained, and there is no resistance to current flow through the cells.

Since the aluminum arresters will continue to discharge until the trouble is removed from a circuit, they should be installed where there is an attendant to note the discharge and take steps to locate the trouble and remove it.

Greater reliability of operation, and longer life of electrolyte and cones can be secured by protecting the arrester tanks from extreme temperatures. When the tanks are installed inside a building it is not difficult to prevent freezing of the electrolyte, which will occur at about 20°F. The high temperatures, however, are to be most guarded against, and when selecting the location for an arrester, the question of possible operating temperatures should be carefully investigated.

When complete arresters are installed out-of-doors, in warm climates, it is generally necessary to erect some sort of a shelter over the tanks to protect them from the direct rays of the sun.

In some extreme cases additional precuations may be necessary, such as water cooling jackets, to prevent undue heating of the electrolyte. When the operating temperature of an arrester exceeds 100°F., the film dissolution increases rapidly thereby reducing the life of the electrolyte and cones. Moreover, when arresters are exposed to high temperature it is generally necessary to charge them more frequently than once a day.

The question of using aluminum arresters out-of-doors at some exposed point of the transmission line, often arises. The use of the arrester under such conditions is bad practice. The arrester can not very well be charged every day, and daily charging is necessary.

The arresters are of little value in protecting the transmission lines themselves. Lightning disturbances are so often purely local in character that the arrester can not protect any particular part of the line.

While this type of lightning arrester is as good as is now available for high potentials, it has certain disadvantages, the principal ones being, first, its maintenance cost is considerable as the aluminum cells are frequently injured by heavy discharges and have to be replaced. Also, since they have to be charged every day, they can be installed only where there are attendants. In addition, the cost of arresters of this kind is considerable.

For wiring high-voltage aluminum arresters, the use of copper tubing is recommended. There are several reasons which make its use advisable:

In all lightning-arrester installations it is necessary to provide a path to the lightning arrester and to the ground with as little impedance as possible. In order to accomplish this purpose, rather large wires with long bends and turns would have to be used. It is well known that high-frequency lightning disturbances are confined largely to the outside surfaces of the conductors, penetrating but little toward the center, hence, by using either flat strip or tubing, the advantage of a large conductor, namely, a large surface, is obtained but at a much lower cost. Copper tubing has the advantage over either strip or solid conductors, in that it is easily supported, requires fewer insulators, and is therefore the cheapest to install. It also presents a neat appearance, since when the wiring is complete, all joints are flush, all sharp bends are eliminated, and there are no points where corona or brush discharges can take place.

Multigap Arrester.—Another successful form of lightning arrester is the "multigap." This arrester is made up of a series of spark gaps, shunted by graded resistances, but without series resistance. Fig. 175 is a diagram illustrating the arrangement of spark gaps and resistances.

The essential elements of the multigap arrester are a number of cylinders spaced with a small air gap between them and placed between line and ground, and between line and line. In operation, the multigap arrester discharges at a much lower voltage than would a single gap having a length equal to the sum of the small gaps.

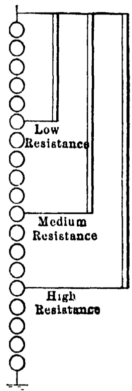


FIG. 175.—Diagrammatic multigap arrester.

In explaining the action of multigaps, there are three subjects to consider:

1. The transmission of the static stress along the line of cylinders.
2. The sparking across the gaps.
3. The action and duration of the generator current which follows the spark, and the extinguishment of the arc.

A spark may be defined as passage of electricity through the air, and an arc as conduction of electricity by vapor of the electrode.

The cylinders of the multigap arrester act like plates of condensers in series. This condenser function is the essential feature of its operation. When a static stress is applied to a series of cylinders between line and ground, the stress is instantly carried from end to end. If the top cylinder is positive it will attract a negative charge on the face of the adjacent cylinder and repel an equal positive charge to the opposite face, and so on, down the entire row. The second cylinder has a definite capacity relative to the third cylinder and also to the ground; consequently the charge induced on the third cylinder will be less than on the second cylinder, due to the fact that only part of the positive charge on the second cylinder induces negative electricity on the third, while the rest of the charge induces negative electricity to the ground. Each successive cylinder, counting from the top of the arrester, will have a slightly smaller change of electricity than the preceding one. The condition has been expressed as, "a steeper potential gradient near the line."

The quantity of electricity induced on the second cylinder is greater than on any lower cylinder and the first gap has a greater potential strain across it than any other gap, as shown by the illustration below. When the potential across the first gap is sufficient to spark, the second cylinder is charged to line potential and the second gap receives the static strain and breaks down. The successive action is similar to overturning a row of ninepins by pushing the first pin against the second. This phenomenon explains why a given length of air gap concentrated in one gap requires more potential to spark across it than the same total

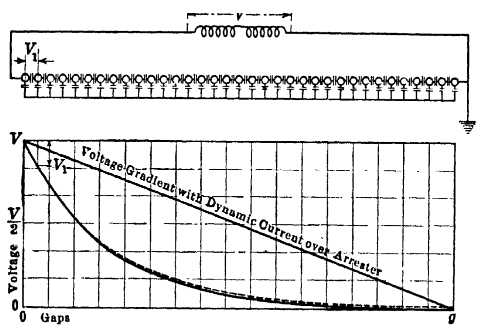


FIG. 176.—Diagram showing condenser action of cylinders and potential gradient for static stress.

length made up of a row of multigaps. As the spark crosses each successive gap, the potential gradient along the remainder readjusts itself. Fig. 176 is a diagram showing the condenser action and the change in the electrostatic gradient.

When the sparks extend across all the gaps the generator current will follow it. On account of the relatively greater generator-current flow, the distribution of potential along the gaps becomes equal, and has the value necessary to maintain the generator-current arc on a gap. The generator current continues to flow until the potential of the generator passes through zero at the next half cycle, when the arc-extinguishing quality of the metal cylinders comes into action. The alloy contains a metal of low boiling point which prevents the reversal of the generator current. It is a rectifying effect, and before the potential again reverses, the arc vapor in the gaps has cooled to a non-conducting state.

This type of arrester may be considered as four arresters in one. First, for small discharges there are a few gaps in series with a high shunt resistance. This part of the arrester will safely discharge accumulated static and also all disruptive discharges of small ampere capacity. In Fig. 177 this path is shown through *H*, (resistance) and *GS* (gaps). Second, there is a number of gaps in series with a medium shunt resistance which will discharge disruptive strokes of moderate ampere capacity; in the figure this path is shown through *M* (resistance) and *GH* plus *GS* (gaps). Third, there is a greater number of gaps in series with a low shunt resistance which will discharge heavy induced strokes. In the figure this path is shown through *L* (resistance) and *GM*, plus *GH*, plus *GS* (gaps). Fourth and last, the total number of gaps has no series resistance, thus enabling discharge of the heaviest induced strokes. In the figure, this path is shown through zero resistance and *GL*, plus *GM*, plus *GH*, plus *GS* (gaps).

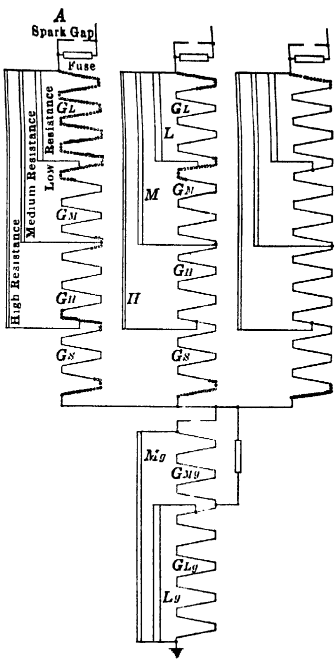


FIG. 177.—Connections of multigap lightning arrester.

In each of the above circuits the number of gaps and the resistance are so proportioned as to extinguish the generator-current arc at the end of the half cycle in which the lightning discharge takes place.

After the spark passes, the current arcs are extinguished in the reversed order. The low resistance, *L*, is proportioned to draw the current arcs instantly from the gaps, *GL*. The generator current continues in the next group of gaps, *GM*, until the end of the half cycle of the generator wave. At this instant the resistance, *M*, aids the rectifying quality of the gaps, *GM*, by shunting out the low-frequency generator current. On account of this

shunting effect the current dies out sooner in the gaps, *GM*, than it otherwise would. In the same manner, but to a less degree, the high resistance, *H*, draws the generator current from the gaps, *GH*. This current now being limited by the high resistance, the

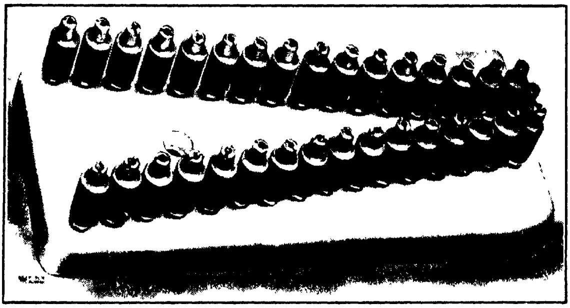


FIG. 178.—"V" unit of multigap lightning arresters.

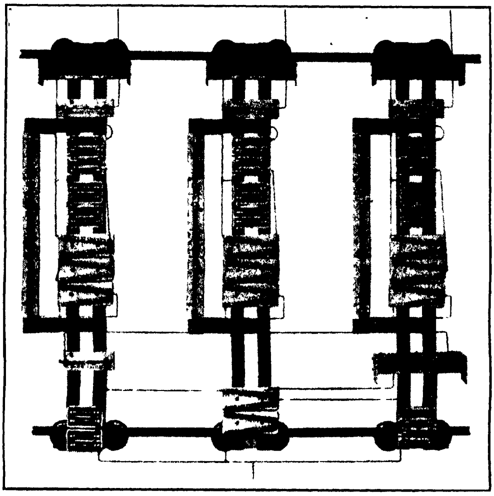


FIG. 179.—12,500 volt, three-phase, multigap lightning arrester with disconnecting switches.

arc is easily extinguished at the end of the next one-half cycle of the generator wave.

The high-voltage multigap arrester is made up of "V" units consisting of gaps between knurled cylinders the units being

connected together at their ends by short metal strips. The base is of porcelain, which provides an insulating support for each cylinder. A unit is shown in Fig. 178 and a complete arrester in Fig. 179.

The cylinders are made of an alloy that contains metal of low boiling point which gives the rectifying effect, and metals of high boiling point which can not vaporize in the presence of the one of low boiling point. The cylinders are heavily knurled. As the arc plays on the point of a knurl it gradually burns back and when the metal of low boiling temperature is used up, the gap is increased at that particular point. The knurling, therefore, insures longer life to the cylinder by forcing successive arcs to shift to a new point. When worn along the entire face the cylinder should be slightly turned.

It is to be noted that in installing multiple gap lightning arresters on high voltage systems, the location of the arrester is important and it should be placed at some distance from any grounded object, otherwise, the potential gradient may be changed and so greatly increased near the top cylinder that discharge may take place under normal line voltages.

Condenser.—The use of condensers, connected directly between the ground and the transmission line, has been suggested and in some cases they have been actually employed for protection of circuits against surges and high frequency charges. The condenser is built to withstand the high potentials to which it will be subjected and its capacity is very low, so that at normal operating frequencies the amount of current passing through it to the line is almost negligible, being, in practice, less than ½ ampere. With the high frequencies of surges and similar electrical disturbances ranging from 5,000 to 1,000,000 cycles per second, the condenser allows a considerable current to flow through it to the ground, thus relieving and clearing the line of these abnormal potentials.

Ground Connections.—In all lightning arrester installations it is of the utmost importance to make proper ground connections, as many lightning arrester troubles can be traced to bad grounds.

The best method of making a ground is to drive a number of 1-in. iron pipes 6 or 8 ft. into the earth surrounding the station, connecting all these pipes together by means of a copper wire or, preferably, by a thin copper strip. A quantity of salt should be placed around each pipe at the surface of the ground and the

pipe should be located where the earth will be kept thoroughly moistened. It is advisable to connect these pipes to the iron framework of the station, and also to any water mains, metal flumes, or trolley rails which are available. For the usual sized station the following recommendation is made: Place three pipes equally spaced near each outside wall, making twelve altogether, and place three extra pipes spaced about 6 ft. apart at a point nearest the arrester.

Where plates are placed in streams of running water, they should be buried in the mud along the bank in preference to being laid in the stream. Streams with rocky bottoms are to be avoided.

Whenever plates are placed at any distance from the arrester, it is necessary also to drive a pipe into the earth directly beneath the arrester, thus making the ground connection as short as possible. Earth plates at a distance can not be depended upon. Long ground wires in a station can not be depended upon unless a lead is carried to the multiple grounding pipes, installed as before described.

As it is advisable to examine the underground connections occasionally to see that they are in proper condition, it is well to keep on file exact plans of the location of ground plates, ground wires and pipes, with a brief description so that the data can be readily referred to.

From time to time the resistance of these ground connections should be measured to determine their condition. The resistance of a single pipe ground in good condition has an average value of about 15 ohms. A simple and satisfactory method of keeping account of the condition of the earth connections is to divide the grounding pipes into two groups and connect each group to the 110-volt lighting circuit with an ammeter in series.

For grounding pole arresters, one or two 1-in., or 1¼-in., iron pipes should be driven into the ground at the base of the pole and connected to the arrester by means of a copper wire not less than No. 2 B. & S. gauge. The ground-wire connection should be protected for some distance up the pole to prevent its being injured. The pipes should be driven far enough from the pole so that movement of the pole will not loosen them.

Choke Coils.—Opinions on the design of choke coils for use with lightning arresters vary considerably. Some engineers recommend the use of very large choke coils, but while large choke

coils of high inductance do choke back the high-frequency currents better than smaller coils of less inductance, they cost more, and, under certain conditions, may be a menace to apparatus insulation. Therefore, large choke coils should not be used without first making a study of the characteristics of the system.

The primary objects of the choke coil should be:

(*a*) To hold back the lightning disturbance from the transformer or generator until the lightning arrester has time to discharge it to earth. If there is no lightning arrester the choke coil evidently can not perform this function.

(*b*) To damp out oscillations of high frequency, so that whatever charge passes through the choke coil will be of too low a frequency to cause a serious rise of potential around the first turns of the end coils in either generator or transformer. Another way of expressing this is from the standpoint of wave-front, namely, a steep wave-front piles up the potential when it meets an inductance. The second function of the choke coil is, then, to smooth out the wave-front of the surge.

It seems best to consider the choke coil as an auxiliary to the lightning arrester. There seems to be no justification for the expense of a very large choke coil. If it has an inductance equal to that of several end turns of apparatus windings it will reduce the steepness of the wave-front of the surge by more than a corresponding value. For example, if there is no choke coil at all, the full strain of a steep wave-front will fall on the end turn. If a choke coil of inductance equal to one end turn is placed in series, this strain will be reduced to one-half. If the choke coil has an inductance equal to six turns, the strain on the end turn will be reduced to about one-seventh. Since a choke coil of such an inductance will have a time constant which is greater than the dielectric spark lag of a modern arrester, the arrester will be in full operation and relieve the strain before the charge can get through the choke coil.

The principal electrical condition to be avoided is that of resonance. The coil should be so designed that if continual surges are set up in the circuit, a resonant voltage due to the presence of the choke coil can not build up at the transformer or generator terminals. This factor is the menace to the insulation before mentioned. Choke coils should be so designed as not to prevent surges which originate in a transformer from passing to the lightning arrester.

See page 254.

Another electrical condition to be avoided in a choke coil, is internal static capacity between adjacent turns, since this lowers the effectiveness of the coil.

Figure 180 shows a choke coil having the well-known "hour-glass" form. Another variety is the standard cylindrical coil, while yet another is made of flat copper ribbon and the cross-section of the coil is triangular, like those shown in Figs. 168 and 169.

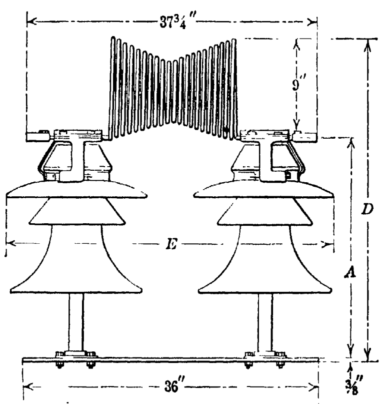


FIG. 180.—"Hour-glass" choke coil.

The following dimensions for cylindrical choke coils are reasonably close approximations to good practice.

6,600 to 10,000 volts, 20 turns, 9 in. diameter.
10,000 to 40,000 volts, 25 turns, 10 in. diameter.

Above 40,000 volts use 10 in. diameter and add one turn for each additional 2,500 volts. Thus, a 66,000-volt coil would have

$$25 + \frac{66{,}000 - 40{,}000}{2{,}500} = 35 \text{ turns.}$$

Clearance between adjacent turns should be not less than ¼ in. and preferably ⅜ in. For rigidity, the diameter of wire should be not less than 0000 B. & S. gauge.

Cylindrical choke coils may be made from bare wire at the point of installation and mounted on standard line insulators, being tied or clamped in place.

Ground Wire.—The ground wire is for the purpose of protecting the line from induced charges or rupturing potentials that proceed from atmospheric electrostatic stresses.

It is simply a wire, usually of iron, strung on the poles, or towers, parallel with the transmission wires but well above them. It is connected, at intervals, with the earth so that the potential of the ground wire is the same as that of the earth. Being placed above the transmission wires, all discharges between the earth and the atmosphere, or clouds, should take place over the ground wire, and the transmission wires thus protected from high and transient pressures that proceed from these causes. In order to be effective, the ground wire must be placed at least 3 ft. above the uppermost wire of a transmission line, and 4 ft. should be its elevation above the top wire, if reasonably practicable. Also, it must be thoroughly connected to the ground at intervals of not exceeding 1000 ft., and an interval of 400 ft. is better.

The ground connection should be made of flat copper tape, having an area equal to a No. 4 B. & S. gauge wire. The same size wire may be used if the tape is not available. The tape is fastened to the ground wire, the joint being soldered; the tape (or wire) being carried down the pole to a grounding pipe. The grounding pipe is the same in size and manner of setting as described in the paragraph on "Ground Connections."

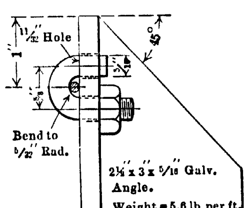


FIG. 181.—U-bolt for clamping ground wire to bayonet.

The ground wire is usually a stranded, galvanized, steel wire 3/8 in. in diameter. It is held on towers by clamping to the uppermost part of the steel work. On wood poles, which project above the highest cross-arm or transmission wire, the ground wire is simply stapled to the top of the pole. Usually, however, the ground wire is fastened to an upwardly projecting support of angle iron, from 2 by 2 in. weighing 3.2 lb. per foot, to 3 by 2½ in. weighing 5.6 lb. per foot. It is held by a U-bolt which clamps the wire to the face of one of the angle legs, as shown in Fig. 181.

The location and arrangement of ground wires are shown in the various figures of pole heads and steel tower lines elsewhere in this book.

Arcing Ground Suppressor.—This instrument, devised by Prof. Creighton, is for the purpose of instantly and automatically extinguishing an arc over insulators or from the line to ground by connecting the arcing line to the earth.

It consists essentially of a set of power-operated single-pole switches, one connected from each phase to ground, the switches being controlled by an automatic relay. The switches are normally open. If a ground occurs on the system, the line potentials become unbalanced, causing movement of the relay which operates to cause the switch connected to the grounded phase to close. This short-circuits the outside ground, and if this ground was caused by an arc to ground, extinguishes it. It will be evident that the arcing ground suppressor can be used only with non-grounded systems, or those having the neutral grounded through a high resistance. The main switch may be an oil switch either motor- or solenoid-operated.

With an overhead system, a large proportion of the grounds are due to arcs over the insulators or from the line to the ground wire which are caused by lightning. The arc, if it holds, will cause serious damage to the lines and insulators, but if extinguished at once, leaves the system uninjured. For use on overhead lines, an attachment called the second-stroke lock device causes the switch to go through the following cycle. When the relay operates, the oil switch closes, and as soon as the motor which operates it can wind up a spring, the spring trips open the switch. If the arc has been permanently extinguished, the relay returns to its normal position and the switch remains open. But if the ground was of a permanent nature, such as a fallen wire or a punctured insulator, the switch closes a second time and remains closed until opened by the operator. Thus, the suppressor is completely automatic for all grounds which can be removed by extinguishing the arc.

It is necessary to prevent any disturbances being produced by the opening and closing of the suppressor switch. To avoid this, the switch is built with an auxiliary contact which closes a little before and opens a little after the main contact. The auxiliary contact connects to ground through a resistance. The switch, therefore, makes or breaks the circuit through a resistance, this resistance being cut out when the main contact is closed.

Figure 182 shows the connections between the high-tension

bus, the winding of the selective relay solenoid, and the ground. This is obviously for one phase only. A similar set of connections is made for each phase.

The relay for controlling the switches is called the phase-selective relay because its function is to pick out the grounded phase. It is operated by the potentials to ground of the system. So long as these are balanced, the relay remains in a neutral or balanced position. But when a ground occurs, the potentials to ground are unbalanced, and the relay moves, closing the contact to operate the proper switch.

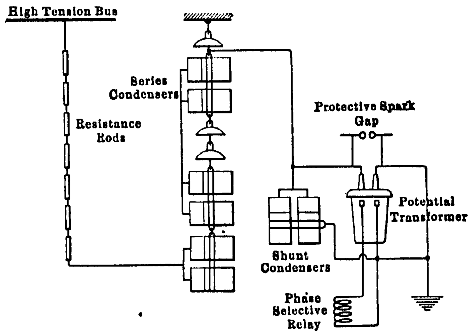


FIG. 182.—Connections for arcing ground suppressor. (One phase only, shown.)

To prevent the possibility of closing two switches at once, thus causing a short-circuit, a relay, called the interlocking relay, is placed between the phase-selective relay and the oil switch. The phase-selective relay causes the interlocking relay to close. The interlocking relay closes a contact in the tripping circuit of the oil switch, causing it to close and, at the same time, opens one of the other contacts in the tripping circuit of each switch, thus making it impossible for them to close.

Spark gaps are also used for the protection of insulators. When excessive potential differences are built up, the natural path of an equalizing discharge through the air is from the wire, over the insulator, jumping from bell to bell, and finally to the insulator pin.

In Fig. 183 is indicated the path which is normally followed by a discharge from wire to insulator pin: from wire *A* to disk *B*; thence to bell 2 and so on, until the pin is finally reached.

The heat released by the arcs, cracks the insulators and interrupts the service. By placing a spark gap at each insulator, with one electrode connected to the line and the other to the pin, and the parts so disposed that any flashover will follow the path between the spark-gap terminals instead of around the bells of the insulator, the danger of breaking the insulators is avoided.

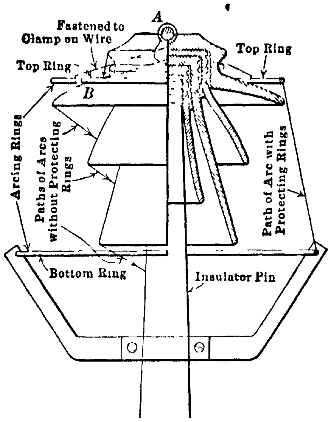


FIG. 183.—Arcing rings.

One form of device for the protection of insulators is the Nicholson arcing ring. A small metallic ring encircles the top of the insulator and is attached to the conductor, while a larger ring surrounds the insulator near the bottom and is electrically connected with the insulator pin, as well as supported on it. The path between the two rings is shorter than that along the insulator bells; consequently, a flashover will take place between the rings,

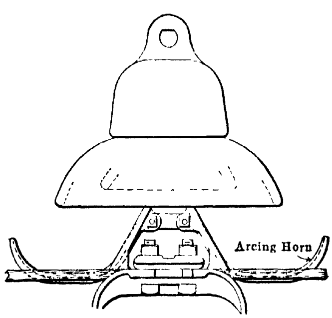


FIG. 184.—Thomas clamp with arcing horn.

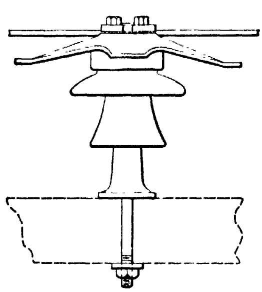


FIG. 185.—Wire clamp with protecting horns.

and the arc will not reach or injure the insulator. Experience, extending over a considerable period, has proven that these devices are effective and afford real protection.

They are also adapted for use on suspension insulators.

A form of spark gap for suspension insulators is the device designed by Mr. P. H. Thomas and shown in Fig. 184.

The "horns," which are connected with the wire, project beyond the limits of the insulator, and, with the uppermost metallic support of the insulator string, form a pair of spark gaps that will shunt any "flashover" away from the insulators themselves.

Other forms of insulator protector gaps have been devised and used. They are always effective when properly designed and installed. As to whether they are worth their extra cost or not, is an economic problem that must be settled for each particular case. The factors of; first cost; maintenance; frequency of electrical storms in the district traversed; whether an overhead ground wire is used or not; character of load at end of line, and the degree of damage sustained by its interruption, must all be duly considered and the conclusion drawn from them.

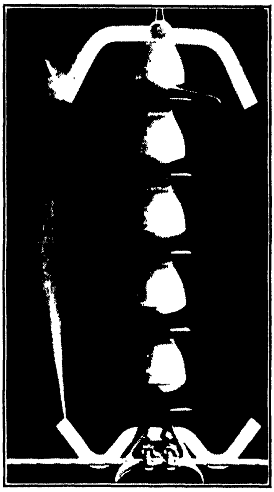


FIG. 186.—Arc passing between arcing horns.

Protectors like the Nicholson ring and the Thomas horn serve to protect both the insulator and the wire itself. A continued arc from the wire will burn it through, and auxiliary projections of metal to interpose themselves between the wire and the arc, will prevent the burning loose of the tie wires or melting of the conducting wire.

Figure 185 shows a device for accomplishing this same purpose for pin-supported insulators. It combines a pair of arcing horns and a clamp to hold the wire without tying. The top cap, which is of steel and into which the four upper bolts are tapped, is cemented to the top of the insulator.

Another form of horn spark gap for suspension insulators is shown in Fig. 186.

Disconnecting Switches.—Transmission lines should be divided into sections ranging from 2 to 10 miles in length, and connected together by air-break switches of some approved kind, which switches are mounted on the pole or tower, and operated from the ground by means of a hook at the end of a long wooden rod or by other means which may depend on the character of the

switch itself. In case of trouble on the line, the sections can be independently disconnected, and the location of the trouble and removal of its cause are facilitated.

An excellent type of switch is the one shown in Fig. 187. The contact is made between a copper block and a laminated copper brush. It is provided with a locking device which holds the switch firmly closed. It rotates in a horizontal plane to open,

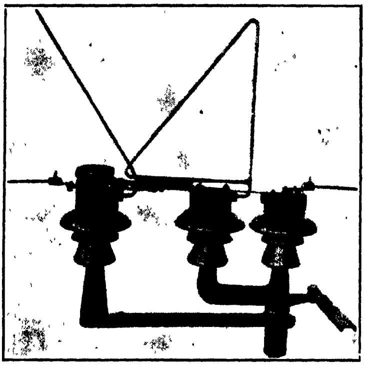


FIG. 187.—Disconnecting switch; horn break.

hence there is no tendency produced by gravity to close it. In opening under load the arc is broken on a pair of horns.

There are, of course, many varieties of disconnecting line switches. Any switch adopted should provide for good contact and a satisfactory means of breaking the arc. It should be firmly locked into position when closed and it should have no tendency to close of itself, when once opened.

CHAPTER XIII

SUBSTATIONS

At points along the transmission line, and at its end, step-down transformers, together with the necessary protective devices and controlling switches, are placed for the purpose of transforming the power to a lower voltage suitable for distribution.

There are three kinds of substations, namely, indoor, outdoor and a combination of these two. The indoor substation is substantially similar to the step-up transformer equipment at the power station, the transformers, switches, high-tension wires and lightning arresters all being placed inside a building which has proper dimensions to house them. Fig. 77, which shows the cross-section through a transformer house for raising the voltage at the power station, may be taken as a typical substation building, there being no real difference between the equipment for a step-up and a step-down station except that in the latter there are, occasionally, distributing switchboards for sending out low-tension current over different feeders. Fig. 188 shows the cross-section of a small substation with the lightning arresters and choke coils set on the roof. A brick or concrete fire wall runs longitudinally through the building, separating the transformers from the rest of the building so that in case the transformer is set on fire, no injury can be done the other apparatus. Placing a portion of the equipment outside of the house is approaching toward a mixed type of substation.

Complete outdoor installations, up to a few hundred kilovolt-amperes, have enabled service to be given to isolated customers and small communities which otherwise could not be profitably served directly off the main transmission lines. It is possible to locate such substations almost anywhere, the structural and foundation requirements varying with conditions. The simplicity of design and construction means a small investment and a minimum of operating troubles. High-tension switching is usually done with air-break instead of the costly oil

switches, while lightning protection is afforded either by the electrolytic lightning arrester or the cruder horn type. Most such installations have been free from elaborate secondary control, that provided, if any, being of the simplest type installed in weatherproof housings. There can be hardly any question as to opportunities for this type of station, and its rapid adoption and extending installation, on account of the

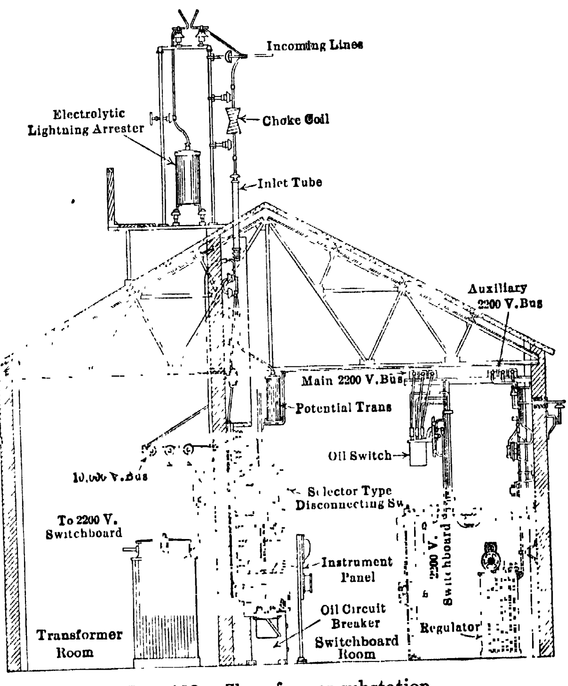


FIG. 188.—Transformer substation.

factors of simplicity, low cost and lack of attendance, indicates the importance of its field.[1]

Outdoor substations have been made possible by the development of transformer cases which have water-tight terminals and joints, and electrolyte for electrolytic lightning arresters which does not freeze except at abnormally low temperatures, and oil-break switches which are encased in water-tight covers.

[1] McCOMBER, "Substations," *Trans.* A. I. E.E., Feb. 25, 1914.

The transformers must be protected from the direct rays of the sun in warm climates. A screening shed is sometimes used, but an outer covering around each transformer is better. This is made of thin sheet iron surrounding the transformer case, there being a clearance of from 8 to 18 in. between the transformer on the outer protecting case. This gives an air space between the two and the heated air rises inside the protecting shell, which, in this manner, acts as a ventilating chimney as

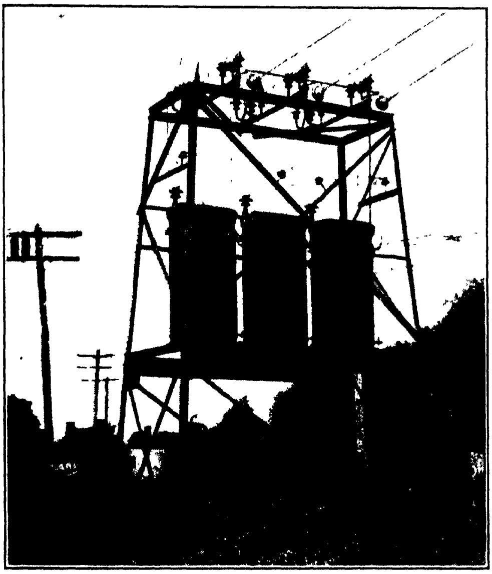


FIG. 189.—Out-door substation.

well as a sun shield. It is, of course, open at the bottom, and there is a space left between the upper end and the cover to allow the free circulation of air.

The horn gaps, choke coils and connections are usually placed on a framework, either of structural steel or timber. If the transformers are small they are generally mounted on a platform supported by the same framework, and at some distance below the top where the horn gaps and coils are mounted. Fig. 189 shows a small out-door station of this kind on a structural-steel

frame. Where the installation is of considerable size, the transformers are placed on a concrete platform laid on the ground. A substation of this kind is shown in Fig. 190. This particular station is provided with self-cooling transformers which have radially projecting wings placed around the case to assist radiation.

An interesting substation is shown in elevation in Fig. 191. The only available place was on a hillside and the ingenious

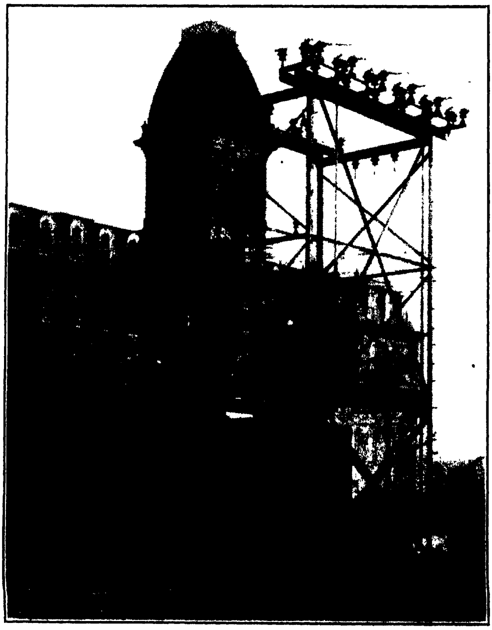


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FIG. 190.—Out-door substation.

manner in which it was utilized is indicated in the figure. Only one wire is shown in this elevation, all three wires being in one horizontal plane. This station is really in duplicate with cross-connections between the two sections.

In cases where there are distributing lines fed from a manually operated switchboard, the board, with its connections, has to be housed, and stations of this character are made up of out-door

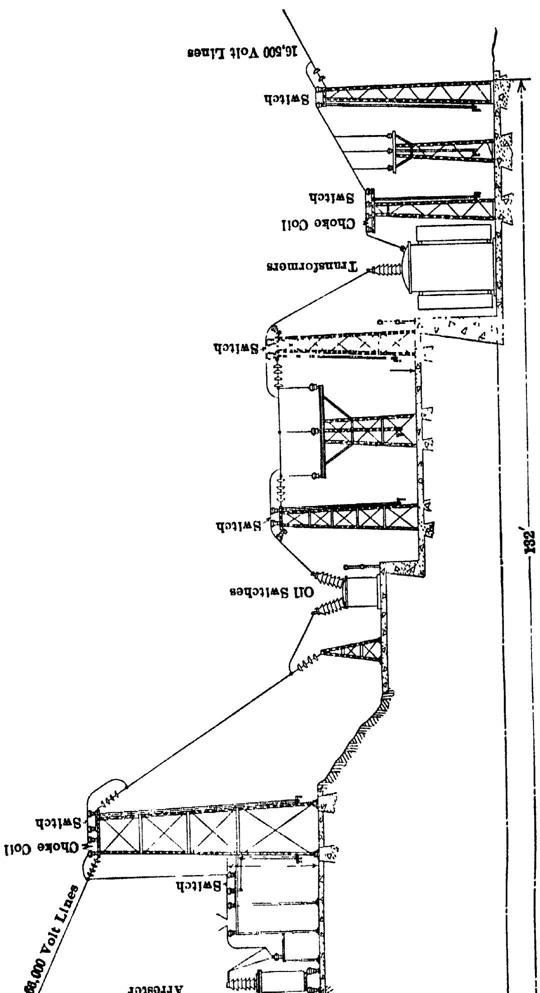

FIG. 191.—Connections of out-door substation.

equipment and a small building adjacent to it for the reception of the apparatus which requires protection. Figs. 192 and 193 show two examples of this character of substation. In both instances the building is made of corrugated iron. Another form of structure which is used for these houses is that shown in Fig. 194. This is made up of a light structural-steel framework and covered with concrete slabs 3 by 6 ft.—2 in. in thickness that are simply bolted on to the framework. These slabs are reinforced

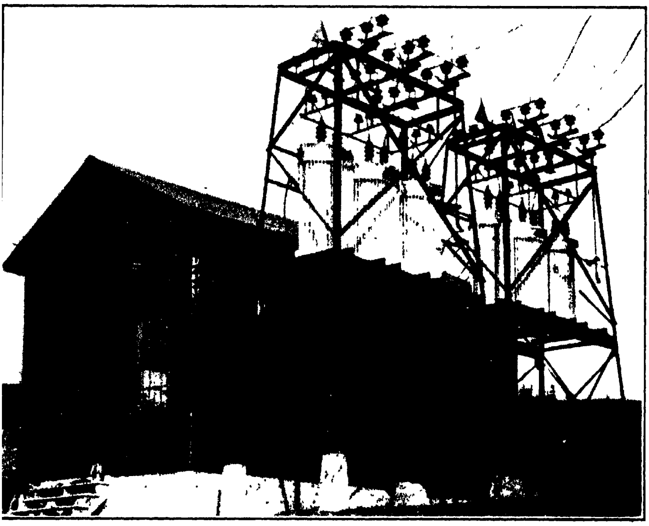

FIG. 192.—Mixed-type substation.

with expanded metal to keep them from cracking. Similar slabs are used for the roof which is covered over with tar paper and gravel. Steel sash, wire-glass windows and steel louvres are used. For air supply, a section of concrete is left off one or two of the lower slabs, leaving the expanded metal reinforcing exposed. This allows a free inlet of air and at the same time prevents large objects from entering.

It is occasionally necessary to provide a stove inside the house, with heating coils arranged to circulate hot water through a small heat coil in the transformer when the temperature becomes lower than 15° below zero F. Down to this temperature the oil will

not freeze, and if the transformers are reasonably well loaded there is no danger of freezing at a temperature of 10° or 15° below this. Special grades of transformer oil are obtainable which will not freeze until the temperature is lower than 25° below zero F.

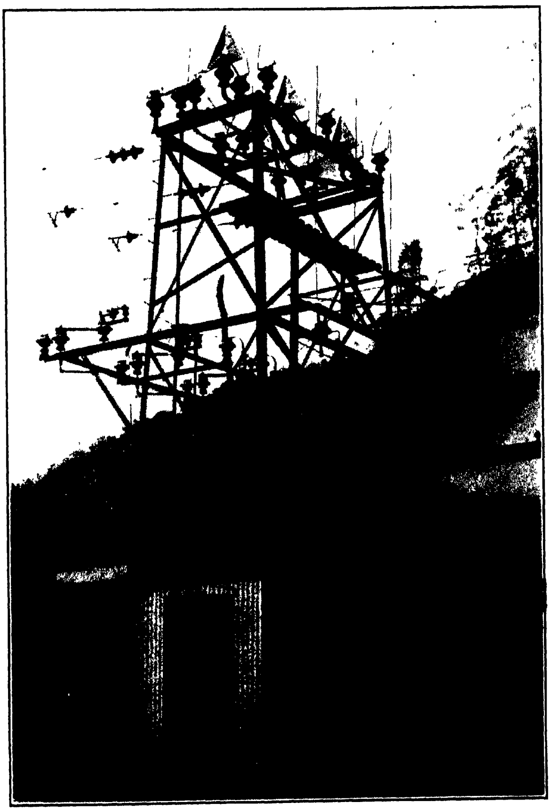

FIG. 193.—Mixed-type substation.

The cost of an out-door substation ranges from 25 to 50 per cent. less than that of an indoor station, and an additional advantage lies in the fact that it can be increased in size at any time and expanded in whatever direction may be most convenient.

Small houses should be built in connection with stations of 1000-kw. capacity or more, for the distributing boards and as a convenient place to make repairs and to store supplies. No

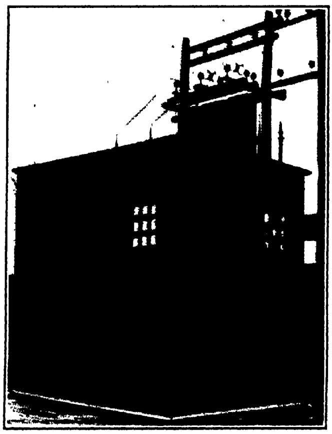

Fig. 194.—Small house for substation.

rules for the design of substations, based on current practice, are available. The best and most economical arrangement can be worked out easily on the ground by any engineer, to accord with the local conditions.

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